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LOW-RESOLUTION SCREENING OF EARLY STAGE ACQUISITION SIMULATION SCENARIO DEVELOPMENT DECISIONS

by

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13. ABSTRACT (maximum 200 words)

The United States Army and the United States Marine Corps currently use Combat XXI as their premier computer simulation for estimating the effects of the introduction of changes to unit composition and equipment on the battlefield. It is a time consuming model to produce and run, in that it represents very detailed and intricate interactions.

Another similar, but less detailed computer simulation is the Dynamic Allocation of Fires and Sensors (DAFS). Instead of modeling the explicit interactions between every soldier and Marine, scenarios can be designed to focus on the effects of combat between groups of combatants. Scenarios can be developed and run faster, but with less insight into the mechanism of interactions.

This thesis explores the possibility of using a low-resolution simulation as a rapid prototyping device for more arduous (and expensive) simulations to gain limited insight and assist in scenario development by contrasting a scenario developed in COMBATXXI with a similar scenario developed in DAFS.

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LOW-RESOLUTION SCREENING OF EARLY STAGE ACQUISITION SIMULATION SCENARIO DEVELOPMENT DECISIONS

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ABSTRACT

The United States Army and the United States Marine Corps currently use COMBATXXI as their premier computer simulation for estimating the effects of the introduction of changes to unit composition and equipment on the battlefield. It is a time consuming model to develop and run, in that it represents very detailed and intricate interactions.

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LIST OF ACRONYMS AND ABBREVIATIONS

AOA	Analysis of Alternatives
ACV	Amphibious Combat Vehicle
CAS	Close Air Support
COA	Course of Action
COMBATXXI	Combined Arms Analysis Tool for the 21st Century
CVO	Constrained Value Optimizer
DAFS	Dynamic Allocation of Fires and Sensors model
GCV	Ground Combat Vehicle
GUI	Graphical User Interface
HTN	Hierarchical Task Network
MCCDC	Marine Corps Combat Development Command
P_{hit}	Probability to hit the intended target
P_{kill}	Probability to kill the intended target
SITS	Scenario Integration Tool Suite
USMC	United States Marine Corps
WSMR	White Sands Missile Range

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There were many people that helped me personally in my efforts to complete this thesis. Though my name may be prominent on the title page, it was certainly a team effort.

I would first like to thank my entire family for their support. My wife Heidi was especially supportive, even though the topic is a foreign language to her ears.   Her gentle urgings helped me through the frustrations.

My two advisors, Dr. Buss and Dr. Balogh were patient and helpful throughout. Regardless of the naivety of my questions, they were willing to work with me through to completion. I recognize that the efforts I asked of them were in addition to their normal requirements and thank them whole-heartedly for their frequent meetings and discussions. I easily learned as much from their insight as from any of the associated research.

The topic was the compilation of several ideas, not least of which came from the folks working at TRAC-MONTEREY. LTCs John Alt and Jason Caldwell both described difficulties they had perceived in working with COMBATXXI and how JDAFS might be used in a similar manner. MAJ Kevin Bolke was kind enough to share some of his experiences working with COMBATXXI while stationed at WSMR, Dr. Tom Anderson was able to help me find a contact at WSMR, Ms. Hinojosa, for some initial data exploration. Ms. Hinojosa then provided me with a fantastic collection of data directly applicable to the study.

In execution, staff at MCCDC OAD helped me immeasurably. Maj Chris Fitzpatrick went through the trouble of helping me acquire the scenario used in this study to include trouble-shooting and modifying it, all on his own time. He patiently helped me through the initial stages of getting a running copy of the scenario on a local machine, without which the study would not have happened. Mr. Al Sawyer advised me in my efforts, while Mr. Ted Roofner provided me with the unclassified weapons data necessary for the contrasting scenario.

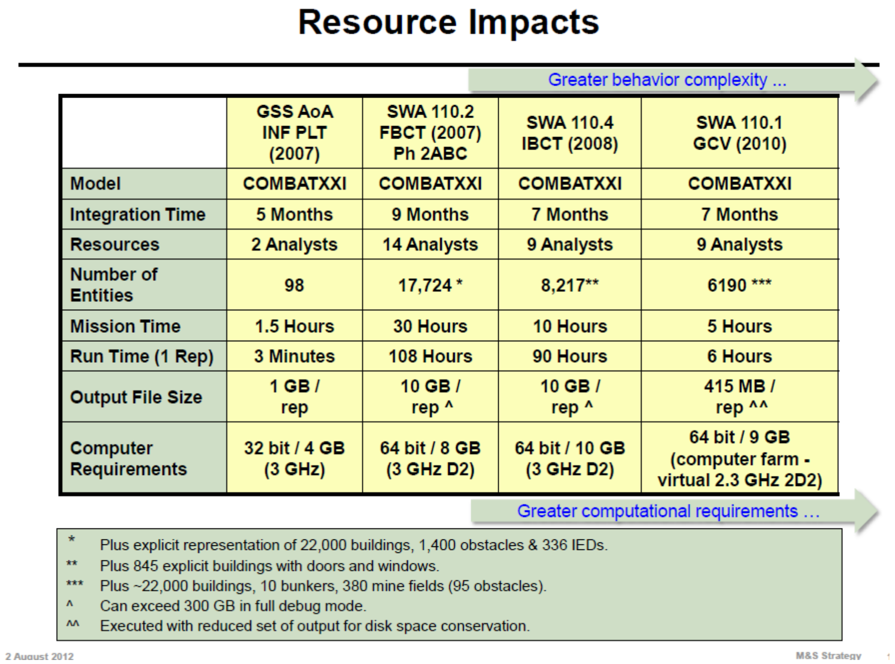
Lastly, I would like to thank my classmate, sometimes opponent, but always my friend, MAJ Brian Vogt. He acted as a sounding board for many of my ideas. His experiences in Army simulation often offered a background for him to critique and debate that helped me develop my concepts.

I. INTRODUCTION

A. BACKGROUND

Simulation has many uses, one of which is analysis for acquisitions decisions. When assessing the value of adding a new weapon system to the existing infrastructure, live-fire field tests are expensive and dangerous to conduct and usually cannot cover the full range of potential operational scenarios. Researching emerging combat technologies and tactics through simulation provides a critical component for conducting a thorough and diverse analysis of alternatives (AOA) prior to committing to large expenditures of taxpayer dollars in acquisitions programs.

Acquisitions analysis through simulation is both difficult and potentially very costly in both time and money. One tool used for such analysis is the simulation COMBATXXI (COMBATXXI), which is used by both the Army and the Marine Corps. The 2012 Analysis of Alternatives (AOA) conducted by the Marine Corps Combat Development Command (MCCDC) on the Amphibious Combat Vehicle (ACV) cost an estimate of $1,281,000 (part of which was the cost of COMBATXXI development and analysis) (Sawyers, personal communication, July 13, 2012). Army personnel at White Sands Missile Range (WSMR) estimated the scenario development time in COMBATXXI for the 2010 study of the new Ground Combat Vehicle (GCV) at 7 months for 9 trained analysts (Figure 1).



Resource Impacts

Greater behavior complexity …

	GSS AoA INF PLT (2007)	SWA 110.2 FBCT (2007) Ph 2ABC	SWA 110.4 IBCT (2008)	SWA 110.1 GCV (2010)
Model	COMBATXXI	COMBATXXI	COMBATXXI	COMBATXXI
Integration Time	5 Months	9 Months	7 Months	7 Months
Resources	2 Analysts	14 Analysts	9 Analysts	9 Analysts
Number of Entities	98	17,724 *	8,217**	6190 ***
Mission Time	1.5 Hours	30 Hours	10 Hours	5 Hours
Run Time (1 Rep)	3 Minutes	108 Hours	90 Hours	6 Hours
Output File Size	1 GB / rep	10 GB / rep ^	10 GB / rep ^	415 MB / rep ^^
Computer Requirements	32 bit / 4 GB (3 GHz)	64 bit / 8 GB (3 GHz D2)	64 bit / 10 GB (3 GHz D2)	64 bit / 9 GB (computer farm - virtual 2.3 GHz 2D2)

*	Plus explicit representation of 22,000 buildings, 1,400 obstacles & 336 IEDs.
**	Plus 845 explicit buildings with doors and windows.
***	Plus ~22,000 buildings, 10 bunkers, 380 mine fields (95 obstacles).
^	Can exceed 300 GB in full debug mode.
^^	Executed with reduced set of output for disk space conservation.

2 August 2012

M&S Strategy

Figure 1. Resource Impacts Associated with Increasing Unit Size (from N. Hinojosa, personal communication, August 9, 2012).

One approach to scenario development and modification in COMBATXXI is achieved through a monolithic development process. This technique implies that scenarios are developed to near completion without much incremental testing. This technique is used because development teams assume there is insufficient time for incremental development (I. Balogh, personal communication, September 5, 2012). One drawback of this technique is that systemic errors are not likely to be discovered until late in the development cycle. With integration issues tightly coupled during late stage development, errors can require retooling on a large scale. Redesigning a simulation scenario with complex behaviors and interactions late in the development cycle costs time and money.

Another technique is evolutionary prototyping. Using this technique, scenarios are developed through a process of creating simple versions, and then continuously expanding from a working model. This is very effective, especially when the model lacks complexity. As the model is developed, however, interactions become progressively more difficult to troubleshoot. This translates into delays in development associated with trial run testing. The incremental runs take longer based on complexity, even when making low-level changes to the scenario. The effects of seemingly minor changes can take hours to assess.

Rapid, throw-away prototyping techniques can be borrowed from other industries in order to address some of these issues. An example of the utility of this technique occurs in the auto industry. Clay, computer, and wooden models are built of cars before the design team even attempts to make a working prototype. The mock-up of the finished product gives the developers insights that eliminate development errors that would otherwise be more costly to correct at later stages of product development. An application of this approach to simulation development is the use of a simplified model to construct a scenario (or portion thereof) as a concept test-bed. The throw-away aspect implies that the model can be used to gain insights, without any expectation of being used in the final solution. Properly implemented, a simplified model can be developed at several points along the model development cycle to rapidly troubleshoot interactions without the difficulties of exploratory development in the actual model.

A simulation must be designed to fill a specific need; there is no one simulation that will be optimal for all tasks. In practice though, simulations are not always used to address the task for which they were designed. Much as a wrench can be used effectively as a hammer, simulations are often called on to perform tasks that are possible, yet not optimal. The results of using the wrong tool for the wrong job manifest in simulations as they do elsewhere. Less than optimal tasking can lead to inefficiencies and disparity in results.

The level of detail modeled in a simulation should be dependent on the problem being addressed. When the results of an interaction are likely to affect the outcome of the experimental metrics, the interactions need to be modeled. Building a model with a greater level of detail is more difficult, and sometimes not related to the experimental question. For example, estimating the number of infantry companies required to take an objective requires one level of detail, while estimating the number and type of munitions required for a specific assault requires a whole additional level of detail.

Simulations can be roughly categorized along a continuum from high-resolution to low-resolution. In high-resolution combat models, interactions and agents are individually described. Explicitly modeling many contributing facet of a system allows for the development of a deeper understanding of that system, especially when dealing with complexity. Interactions, once recognized in analysis, can then be further explored. In attempting to represent many interactions in a complex system, high-resolution simulations, such as COMBATXXI, can be slow to develop, trouble-shoot, execute, and analyze.

In low-resolution models, effects and or agents are abstracted such that many interactions are simplified or covered by assumption. The effects of interactions can be recognized and effectively modeled in a low-resolution context without modeling the mechanism of such interactions, especially when the purpose of the simulation does not require the investigation of such a level of detail. Low-resolution models use relatively simple mathematical models to represent interactions, making calculation simpler. Troubleshooting errors and running such a simulation takes significantly less time and effort. Thus scenarios can be rapidly developed and produce sufficient results for usable statistical analysis. It can be an especially helpful technique to use when the effects are historically well documented. One such simulation is the Dynamic Allocation of Fires and Sensors (DAFS) model. "DAFS is an entity-level simulation framework that adopts a 'low-resolution' world view. It is intended for situations requiring fast turnaround analysis and those requiring much flexibility and customization on the part of the model." (DAFS User Guide, September 2012).

When a situation arises that requires simulation experimentation in a short time span, a low-resolution simulation such as DAFS can quickly produce results. These results lack the details inherit in the higher resolution models, but the results of low-resolution analysis often complement the more deliberate research associated with more complex modeling efforts.

B. PROBLEM DEFFINITION

Scenario development in COMBATXXI can be time consuming and expensive. Complex modeling of interactions often generates initial erroneous results that are difficult to troubleshoot. Running the model can take long periods of time, even when troubleshooting. It can postpone the development of final analysis products and reduce the time available to perform run-time variations for different courses of action (COAs). Recognizing that COMBATXXI is one of the models currently used for developing the AOAs critical to multi-million or billion dollar acquisitions choices, can the use of DAFS provide a low overhead method to decrease scenario production cycle times and costs as a rapid, throw-away, prototype? What are the potential pitfalls associated with attempting to translate data from one model to another?

Though the results of a low-resolution simulation are less detailed concerning interactions, can the results of a low-resolution simulation such as DAFS provide an adequate rapid turn-around “quick look” into the potential outcome for a high-resolution simulation such as COMBATXXI?

C. THESIS ORGANIZATION

The remainder of this thesis is organized as follows:

- An exploration of concepts, previous work and the models used in this study.
- A preliminary exploration into low-resolution unit aggregation phenomenon.
- An explaination of the methodologies used in conducting the study.
- The results of the study including conclusions.
- Potential areas for future study.

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II. CONCEPTS AND PREVIOUS WORK

This section discusses concepts integral to the study as well as related work in the area. It also highlights the simulations used to conduct this study.

A. SIMULATION RESOLUTION

Consider resolution with respect to simulations as a means of describing the amount of detail explicitly described by a model. Different models can represent the same phenomenon at different levels of detail. Lack of detail does not necessarily imply lack of accuracy. Some very complex interactions can be described by relatively simple models. Differences in representation due to level of detail can lead to dissimilar results, however. As a simple case for comparison, deviation in altitude may be represented at different intervals (i.e. 5m terrain vs. 50m terrain). This disparity can lead to confusing or confounding results. Agents in one model of lower resolution can establish line of sight and engage enemy units, while these same agents would not do so in a higher resolution model due to terrain interference that simply was not represented in the lower resolution model (Figure 2).

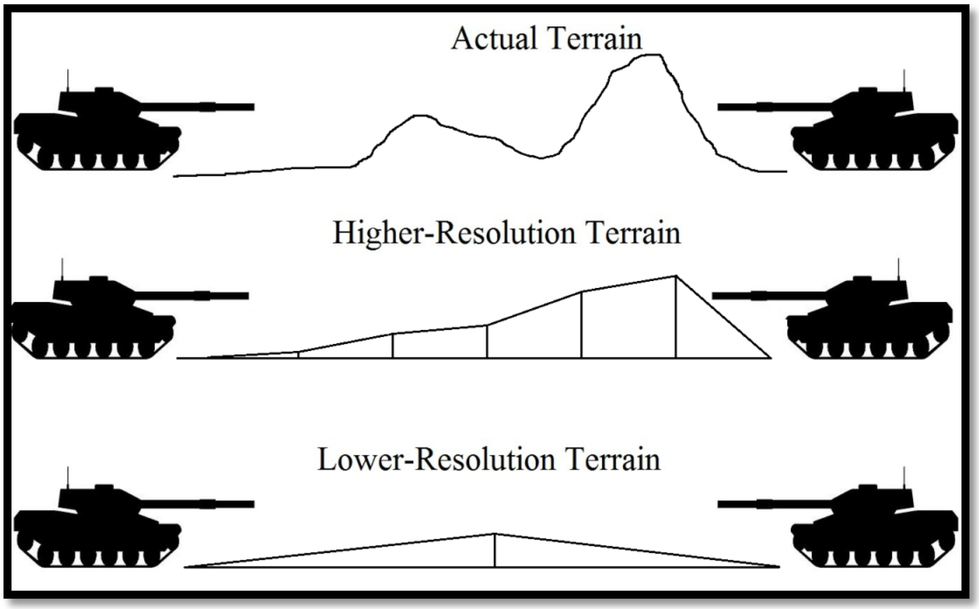


Figure 2. Effects of Resolution on Line of Sight Calculations

This concept of variable levels of detail used in the depiction of entities and phenomenon in simulation extends well beyond terrain. The probability of events is modeled in different ways as well. Much as modeling terrain at high levels of detail is similar to recognizing deviations at small intervals, event probabilities can be estimated by assessing the likelihood of all of the required subtasks occurring in the proper order at the proper time. Events can likewise be defined in a low-resolution manner by simply estimating the probability of occurrence (without decomposing them into subtasks).

1. Contrasting High and Low Resolution in Simulation

Simulation resolution decisions are integral to the problem being studied through simulation. For example, if we assess that terrain data for individual ground combat is significant at a level such that vertical deviations at every 4 inches need to be modeled accurately in order to represent the micro terrain that infantrymen seek for cover from enemy fire, analysts may successfully gain significant insight in modeling a small unit of infantry in a firefight. That same technique could not be used as effectively in modeling campaign size elements in a specific mountainous terrain that spanned hundreds of square miles. The cost (both in computation and storage space) associated with accurately modeling the real world to that level would be prohibitively expensive. Depending on the purpose of the research, modeling such detail may not necessarily provide any additional insight or benefits. The effects of terrain on campaign size elements could possibly be estimated and applied without a significant difference in results. Given a sufficiently large sample of measurements, deviations can be represented by an average or representative distribution.

Higher resolution models can explore the effects associated with interactions, because details of interactions of interest are explicitly modeled. By collecting the data necessary to develop situations adequately, unique and emergent behaviors manifest that allow analysts to develop insight into poorly understood processes. Without the effort to understand complex interactions, we cannot otherwise anticipate how systemic changes will manifest. Sometimes it is impossible to initially determine which factors affect changes in the targeted metrics of consideration due to the complexity of interactions.

Therefore, high-resolution agent-based modeling often trends toward modeling the human cognitive process with the goal of developing agents who act correctly in the presence of a variety of stimuli. Based on the type and amount of data collection necessary to span the problem space, model development can be both extremely complex and time consuming.

Lower resolution models tend to explore relationships through effects-based modeling of more abstract concepts. For example, a low-resolution model may portray a group of Marines as an individual agent such that the goals, abilities, and fate of the group is extended to be that of all the members of the group. In a higher-resolution model, that same group of Marines could be modeled individually with each individual having specific qualities, even to the degree that each agent could have different goals or personalities. Some data is collected at a lower resolution as well, making high-resolution analysis either more difficult or even impossible. For example, historical reports focus on easily defined metrics such as the winner or loser, the casualties, and the time of the event without capturing the high-resolution focus on individual traits or motives.

Below is a paraphrasing of how Paul Davis of RAND discussed the concept of resolution (Davis, 1995). Resolution can be a factor of:

- More fine-grained entities (companies rather than battalions as the individual agents)
- Richness of the attributes associated with each entity
- Relationships and logical dependencies
- How changes in state are managed for entities (damage may be evenly apportioned to all units involved in a battle, or explicitly apportioned based on position)
- Spatial grid and time step, or the discrete-event equivalent (as a measure of complexity in the state change process)

2. Simulation Resolution by General Purpose

Though simulation resolution can vary within a model based on the purpose of the model (higher resolution details in some aspects and lower resolution details in others), a simplistic general differentiation by model purpose can be made (Davis, 1995).

Low-Resolution	High-Resolution
Initial exploration	Understanding phenomena
Comprehension (forest rather than the trees)	Representing knowledge (or skill sets)
System analysis	Simulating reality
Decision support	Calibrating lower-resolution models
Rapid, low cost analysis	When high resolution data is available
When only low-resolution data is available	

Table 1. Simulation resolution based on general purpose (after Davis, 1995)

An important possible characteristic of these generalities is that low-resolution model results can be more easily understood (high transparency). High-resolution models tend to focus on the vagaries of complex interactions, which can produce complex results that may be difficult to understand or explain in the frame of root cause (low transparency). For example, a simplistic model may recognize that an infantryman can detect a tank, without modeling the "how". The detection can be easily traced to a moment in time and results flow naturally from there. In a higher resolution model that represents aural, visual, and networked communication cuing, recognizing that hearing a tank leads to detection but not identification can be an interesting focus that leads to further investigation. How those mechanisms are connected to the results of a conflict may not be easy to understand or explain.

3. Abstraction: Aggregation and Disaggregation

Logically, data must usually be abstracted in some manner to make useful, timely analysis. It would be unreasonable to create a molecular level model that detailed each mote of dust for an operational combat analysis. The level to which data is abstracted affects the results in different ways and every simulation makes assumptions at some level. The information necessary to develop a model of increasingly finer resolution is more expensive to collect in time and money, and never completely correct. At some atomic level of detail, components cannot reasonably be broken down into further sub components. Assumptions exist in every model (i.e. every human has two arms and legs, all aircraft are full mission capable at the start of a sortie, the weather is the same for the entire battlefield, etc.) at different levels of detail. Where low-resolution models make clear and explicit assumptions, the assumptions made at finer points in high-resolution simulations are just as systemic and critical to model success. Those assumptions do not necessarily degrade the value of the insight that can be gained, but must be considered lest some artifacts of these assumptions be taken as fact. "…All models are wrong, but some are useful" (Box, 1987).

The use of assumptions of homogeneity, or the application of a single distribution of characteristics, is a basis for simplifications found in lower resolution models. A classic model for combat is the Lanchester equations. Lanchester's basic models for combat are mathematical equations for determining the outcome of battle based on the size and quality of the forces involved (very low-resolution). One assumption in the original models was that of homogeneity; all of the units of a particular force are assumed to be identical. The basic model was later enriched to account for heterogeneous forces, but the original models develop an interesting concept. Homogeneity is never the case in reality, though at some point the individual differences in each soldier or Marine become less significant to the outcome of the conflict. The average performance of the individuals involved is essentially equal to that of individuals in similar units when viewed on a large enough scale. This is reflected in the concept of the central limit theorem in statistics; that the average value of multiple samples from the same population will be normally distributed about a mean (regardless of the distribution of the population value). These basic combat models were deterministic, which produced a mean value without the associated distribution of values. The distribution of those values about the mean is a necessary component of any sensitivity analysis. Through the use of stochastic modeling (implying an element of chance), the distributions become evident. By accurately reflecting the probabilistic tendencies in events, models can also answer questions concerning the likely magnitude of deviation from the expected mean results.

With an assumption of homogeneity, similar units or effects can be aggregated, but aggregation is a controversial subject. Historically, numerical superiority references of forces were sometimes the only available data, leading to coarser analysis with many assumptions and without due consideration to the individual capabilities of different units. Understanding of cause and effect at the individual combatant level was either unknown or not well recorded. Although a mostly homogeneous force can be more easily assessed and assigned some value representing the collective combat power, forces have become more heterogeneous with units having particular strengths and weaknesses associated with particulars of situations and the opponents they face (Hillestad & Juncosa, 1995). For example, how do you assess the aggregated value of a special operations team? If the team is caught in the open in conflict with an infantry company, they may not fare much better than an experienced fire team. That same force could account for a strategic level of impact given the right opportunities. The controversy over combat power assignment can be decomposed and demystified when disaggregated in a high-resolution model.

Likewise, disaggregation (or decomposition) is not always possible or desired. Though effects may be clearly evident and well understood, data concerning the root cause of effects may not be available (or easily attainable). Determining all of the factors that produce a given set of effects is complicated. Even though individual, lower level interactions may be verified against real world data, the sum of the parts must likewise be so validated. With the integration of complex interactions explicitly designed, it can be difficult to “tune” a model to reflect reality.

B. COMPUTATIONAL COMPLEXITY IN SIMULATION

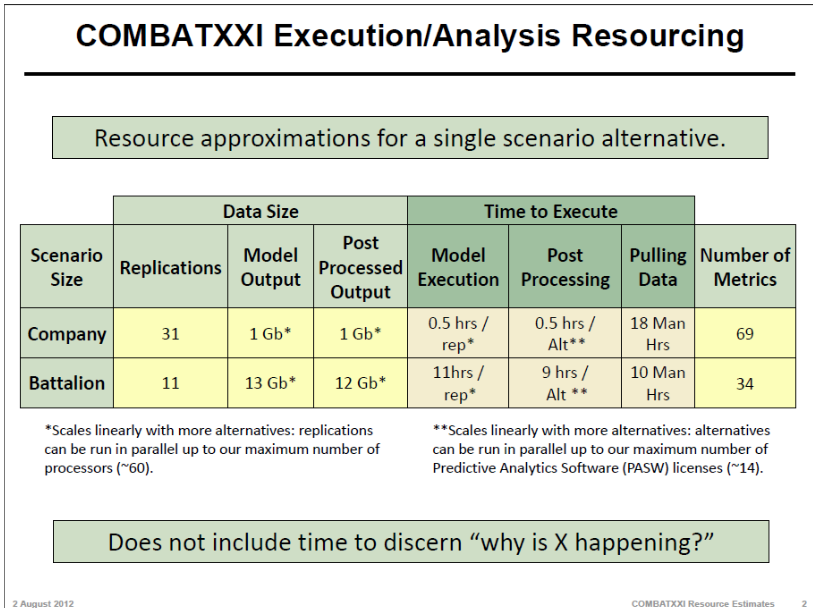
As the mechanics of interactions between entities are further decomposed in more complex simulations, more variables and intermediate computations are added to the calculation of the results of interactions. Thus, increased complexity requires more computing power. As each additional agent is explicitly represented, so more agents are able to interact. This results in a compounding of scenario creation, run-time, data collection, and analysis computational requirements.

More complex models are more difficult to analyze as well. The term "transparency" is used to describe how easily a model's inner workings can be described for troubleshooting or analysis. As complexity increases, model transparency goes down. "Beware of general purpose, grandiose models that try to incorporate practically everything. Such models are difficult to validate, to interpret, to calibrate statistically and, most importantly to explain," (Raiffa, 1982). This can introduce a host of difficulties not present in more simplistic models.

Where more simplistic models offer transparency to the analysts and developers, complex models may offer a sense of false security to decision makers. Complex models are more believable, especially to the uninitiated. If based on the proper theories and data, simple and complex models of the same system should provide similar results. Though the data may reflect similar results, it is assumed that the additional factors available for consideration in the complex models make the results somehow more accurate or better reflections of reality. This is not necessarily the case. "A complex model when shown to managers has more impact than a simpler one, even if they both could perform the same job. Furthermore since it is more complex it has a connotation that it was more difficult to build, valorizing in some sense the modeler's job," (Chwif, Paul, & Pereira-Barretto, 2000).

A good example of the effects of complexity on development and analysis requirements can be seen in Figure 3. Past experience in building scenarios in COMBATXXI has shown that the model can becomes intractable if brigade or large units are modeled. As units of increasing command structures are added to a simulation in

COMBATXXI, additional control measures need to be considered. For example, the communications, route, and behaviors required to describe a platoon element are simplistic when compared to that of a battalion, which requires artillery, air support, and advanced communications networks to be modeled (K. Bolke, personal communication, July 31, 2012). An important point of note is that though every interaction previously included in smaller units is still modeled in the larger unit scenario, the number of metrics analyzed is smaller: from 69 to 34 (likely as a factor of the increased amount of time necessary to process the data).



COMBATXXI Execution/Analysis Resourcing

Resource approximations for a single scenario alternative.

	Data Size			Time to Execute			
Scenario Size	Replications	Model Output	Post Processed Output	Model Execution	Post Processing	Pulling Data	Number of Metrics
Company	31	1 Gb*	1 Gb*	0.5 hrs / rep*	0.5 hrs / Alt**	18 Man Hrs	69
Battalion	11	13 Gb*	12 Gb*	11hrs / rep*	9 hrs / Alt **	10 Man Hrs	34

*Scales linearly with more alternatives: replications can be run in parallel up to our maximum number of processors (~60).

**Scales linearly with more alternatives: alternatives can be run in parallel up to our maximum number of Predictive Analytics Software (PASW) licenses (~14).

Does not include time to discern “why is X happening?”

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COMBATXXI Resource Estimates 2

Figure 3. Resources required as a factor of simulated unit size (from N. Hinojosa, personal communication, August 9, 2012)

When running a model during development, undesired interaction effects become more difficult to diagnose (from Figure 3, “why is X happening”). It becomes increasingly difficult to troubleshoot simulations as the complexity is increased. It may seem that adding more analysts would decrease development and analysis times, which is true to a point. Much as the interactions between agents slow a simulation when more agents are added, the addition of more analysts or simulation developers eventually becomes counter-productive in that additional cross coordination will outweigh the benefit of additional manpower. This effect was well documented with regards to addition of programmers when developing computer code (Brooks, F. P., 1995). This also affects the number of alternative COAs that can be analyzed in a given amount of time.

C. PROTOTYPING

One of the most common prototyping methods in use in software and simulation development is that of evolutionary prototyping. This refers to the creation of a robust, working prototype based on well understood requirements that is to become the finished product through gradual improvement (Davis, A. M., 1992). Evolutionary prototyping with regards to simulation refers to the technique of developing a large, complex model from a simple working model by increasingly adding features while incorporating incremental testing. Though not specifically titled as such, Pidd comments on this technique in reference to effective model development techniques, “Be parsimonious, start small, then add,” (Pidd, M., 1996).

A contrasting technique is known as throw-away prototyping. When developing through the use of throw-away prototyping, poorly understood requirements are modeled separately, with no intent to include the results into the finished results. The models are built solely to gain insight into a portion of the problem, without attempting to integrate any design points directly. “Throwaway prototypes work very well in isolation to verify relatively small parts of complex problems,” (Davis, 1992). Throw-away prototyping is especially useful in exploring poorly understood requirements. This allows for the exploration of the problem space without corruption of the final study development effort and the benefit of timely sidebar analysis.

Acknowledging that scenario development is an incremental art and also that many scenarios offer degrees of reuse, there is some potential for using a simplified simulation or “sand-table” to wargame scenarios to increase efficiency. Much as an artist might sketch ideas separate from the canvas on which he intends his final work, simulation scenarios can be developed separately from the modeling platform on which they are intended to be used. Simplistic, but valuable insight gained through quickly developed models can potentially decrease development cycle times, save effort previously allocated to troubleshooting, and increase overall efficiency. In such a case where the intent is to develop a large, complex constructive situation to evaluate the effects of a new combat system (such as the ACV AOA recently conducted at MCCDC), using a greatly simplified model to gain limited insight into developmental problems may allow more COAs to receive the benefit of early feasibility testing for potential inclusion in the final model evaluation with only a fractional allocation of effort.

D. ESTABLISHING SIMULATION INITIAL CONDITIONS

One avenue previously considered is that of development of simulation initial conditions. Initial conditions in a simulation are those conditions on the battlefield when the simulation begins. Scenarios rarely begin prior to contact; there is usually some sense of how the battlefield was prepared. There might be generated intelligence reports, damage to enemy positions due to preparatory fires, or the assumption that the amphibious force makes landfall prior to the simulation beginning. In practice, subject matter experts are called upon to estimate these conditions. Even the best available experts may have a shallow or dated knowledge on extremely infrequent events. For example, the United States has not taken part in a large-scale, opposed amphibious landing since World War II. There is effectively no first-hand experience with current systems interactions available to support expert evaluations in that realm and many others. Low-resolution simulations may offer a partial answer to fill such gaps.

Similarly, initial conditions are a critical component of mission decomposition. When a mission can effectively be broken into steps or phases, then each phase effectively has different initial conditions. JDAFS (a joint version of DAFS) was proposed as a means for exploring various settings for starting conditions (Ahner, Buss, & Ruck, 2007), but no attempt was made to implement DAFS in such a capacity. If nothing else, initial fuel loads, velocities, orientations, preliminary attrition, and initial sensor targets could be run through a low-resolution trial to confirm not only their validity, but also their possibility. Subject matter expert opinions can thereby be given some level of additional rigorous examination.

E. COMBATXXI

The United States Army and the United States Marine Corps (USMC) use computer based simulations to develop their respective needs in current and future acquisition programs. One simulation currently in use is COMBATXXI. It is an agent based, discrete event, stochastic simulation that can be configured to capture many details associated with modern combat. It can take a significant amount of time to thoroughly develop, run, and analyze a scenario in COMBATXXI.

1. Model Description

The COMBATXXI users' guide available through the WSMR Confluence site (https://COMBATXXI.wsmr.army.mil/confluence/display/COMBATXXIDOC) describes the simulation as follows:

Combined Arms Analysis Tool for the 21st Century (COMBATXXI) is:

- A Joint, high-resolution, closed-form, stochastic, discrete event, entity level structure analytical combat simulation.
- Developed and supported by the TRADOC Analysis Center-White Sands Missile Range (TRAC-WSMR) and other collaborating/partnering organizations.
- Designed for simulation of operations at the brigade level or lower with appropriate representation of Joint/higher echelon assets.
- Used for land and amphibious warfare analyses in the Research, Development and Acquisition (RDA) and Advanced Concepts and Requirements (ACR) Modeling and Simulation (M&S) domains.

Major Model Function includes:

- Ground Combat: Light and Heavy forces.
- Air mobile forces.
- Future forces.
- Fixed-wing and Rotary-wing: CAS, Armed recon, Detailed communications modeling, Rotary-wing, and Direct/indirect fire.
- Amphibious operations.

- Urban operations.
- CSS – logistics and casualty handling.

The Goal of COMBATXXI is to provide:

- A simulation with the needed resolution to model the complex, diverse elements of the operational space of the future.
- A simulation that can represent information flow in a way that allows the analysis of its impact on operational effectiveness.
- USMC with organic analysis tool, with Amphibious and Aviation warfare.
- Large force representations (context) for other models.

2. Scenario Development

Scenario development in COMBATXXI can be very time consuming. Though scenario libraries are available through local servers and on the cloud at sites such as that hosted by WSMR, each scenario must be reviewed in its entirety prior to use as an analysis tool. Debugging complex interactions takes time.

COMBATXXI offers a scenario creation graphical user interface (GUI) for scenario generation. This allows for step-by-step scenario creation and attribution of behaviors to each entity or entity group. The process is work-flow oriented in that developers are intended to follow a logical order of events to efficiently create scenarios (https://COMBATXXI.wsmr.army.mil/confluence/display/ COMBATXXIDOC) by proceeding through the steps in order:

- Designate Resources – performance data, maps, comms, etc.
- Designate Meta Data – properties and parameters of the scenario (study name, terrain, weather, etc.)
- Assign Force Structure – sides, hierarchy of command, entities, etc.
- Design Map/Play board – assign start positions, waypoints, and insert structures.
- Communications – networks and assignments.

- Orders – coordinating maneuvers and assigning behaviors/triggers

This allows for scripting of behaviors similar to a finite state automata where simple rules govern the condition of each entity and act as triggers to change the condition of the entity. In describing the behaviors of the agents, the modelers attempt to represent key decision points for these agents. These decision points represent the interactions in the model. Through the scripting of particular behaviors, modelers attempt to mirror the decision making abilities of entities on the battlefield. In order to correctly design behaviors, the modeler must have available a consummate understanding of the task at hand. COMBATXXI has a large existing library of basic behaviors, but more complex or unique behaviors can be created through creative scripting.

A second methodology for defining behaviors has been developed at NPS that is based on hierarchical task networks (HTNs) (Fitzpatrick, Balogh, and Reeves, 2012). HTNs are best described as tasks decomposed and ordered according to their triggers and frequency. "A plan is then formulated by repeatedly decomposing tasks into smaller and smaller subtasks until primitive, executable tasks are reached. A primary reason behind HTN's success is that its task networks capture useful procedural control knowledge...described in terms of a decomposition of subtasks. Such control knowledge can significantly reduce the search space for a plan while also ensuring that the plans follow one of the stipulated courses of action," (Sohrabi, Baier, McIlraith, 2009). This new methodology promises to provide a more structured way to build behaviors in the future that may ease some of the difficulties with the scenario construction process.

3. Data Analysis

Data analysis for a detailed scenario in COMBATXXI is no trivial task. Through the use of post-processing software, initial analysis is streamlined. The sheer volume of data potentially available following successful runs is daunting (12 GB in figure 3 post-processing complete for a battalion), but because COMBATXXI has different data logging functions for different interactions, the data can more easily be parsed to different analysts.

F. DAFS

Similar to COMBATXXI, DAFS is an agent based, discrete event, stochastic simulation. Both models were developed using the SimKit discrete event methodology. DAFS was designed to allow for lower resolution, rapid model development.

1. Model Description

> DAFS is an entity-level simulation framework that adopts a "low-resolution" world view. It is intended for situations requiring fast turnaround analysis and those requiring much flexibility and customization on the part of the model. DAFS was not intended as a substitute for high-resolution simulations, but rather as a complement to such models. One envisioned use for DAFS that was is to use it as a platform for initial tests and exploration of scenarios. Its ability to rapidly create and modify new scenarios makes it ideal for this task. Its low-resolution approach leads to fast execution times, which enable the analyst to quickly explore the parameter space for the desired situation before investing the non-trivial amount of effort required to develop a higher resolution model. (https://soteria.nps.navy.mil/jdafs/docs/DAFSUserGuide.doc)

2. Scenario Development

Lacking some of the elegance associated with COMBATXXI's development GUI, DAFS potentially requires some degree of computer coding in order to completely develop a scenario. Individual entities are created, and all are basically the same type of entity to which attributes are attached, such as name, type, sensors, munitions, speed, etc. Unlike COMBATXXI, where the internal makeup of units must be explicitly represented, DAFS does not enforce explicit representation. Representation in DAFS can be defined by the scenario developer. Thus the aggregation of units in number and effects can more easily be represented in DAFS. To attempt to model a large number of different units with different behaviors would be difficult in DAFS and require a significant amount of imagination.

DAFS models behavior relatively simplistically in contrast to COMBATXXI. It has the functionality available to compile a low-resolution acquire algorithm associated with the probability to detect enemy units based on scenario variables. DAFS is dynamic in the use of a constrained value optimizer (CVO). This allows agents to find the near-term solution that offers the best local chance of success. In essence, the CVO solves a linear program for each side involved in a battle, so that the fires are directed toward optimal targets while giving credence to the defender’s ability to destroy the attacker. This technique is applied to both sensors and fires. One parameter available for adjustment is the rate at which the CVO executes optimization (and reallocates sensors and fires).

3. Data Analysis

The graphical and data output from DAFS are somewhat limited, though simple enough that with some basic Java experience, modifications are possible based on the study design requirements. There is no innate data analysis capability associated with the suite, though the output is easily imported to commercial data analysis programs such as Excel, R, or JMP.

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III. PRELIMINARY EXPLORATION INTO THE EFFECTS OF UNIT AGGREGATION

As part of an initial exploration into the concept of aggregation, a model was created based on the same basic construct of both COMBATXXI and DAFS: constructive, agent based, stochastic, discrete event, and built based on SimKit. The Battle of Agincourt that occurred on 25 October, 1415 was modeled due to the interesting nature of the results. French forces with an apparent overwhelming advantage were almost completely destroyed or captured by a smaller English force (which suffered almost no casualties). The English were tired, sick, and hungry while the French were fighting close to home.

The battle took place on a wide field in France. The English were able to displace from their defenses and re-establish a position close to the enemy lines, putting the French within the extreme range of the English Longbow. This prompted the French to advance on the English position. The French were not able to flank the English ranks with their cavalry, and the French infantry was unable to close ranks with the English fast enough to avoid significant attrition. The end result was that as few as 450 English died during the battle with the French forces left in shambles.

1. The Model

The model was developed as a low resolution model with both units and effects aggregated to expedite analysis and enable various COAs to be analyzed. The force structure was estimated due to some disparity between accounts of the forces present. As the model was designed, the French forces numbered 13,200 while the English forces numbered 8,500 with a proposed force structure as indicated in Table 2 (most of which were long-bowmen) (http://en.wikipedia.org/wiki/Battle_of_Agincourt).

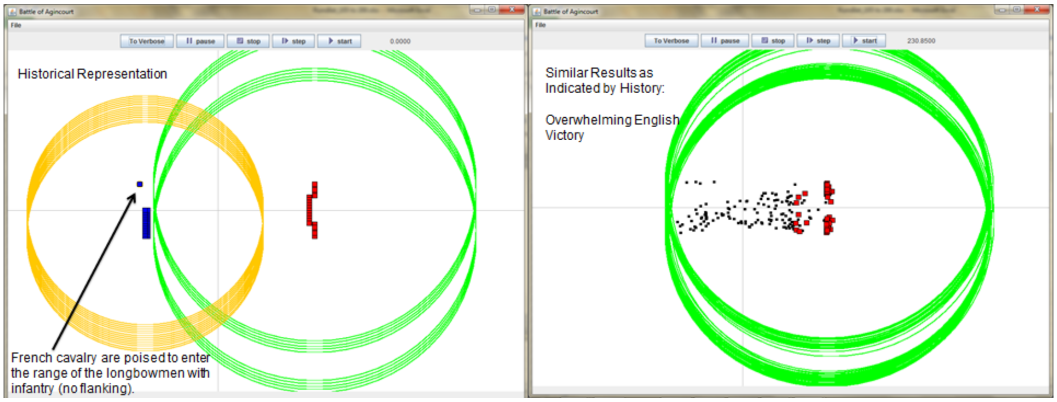
Unit	English	French
Foot Soldiers	1,500	8,000
Calvary	0	1,200
Bowmen	7,000	4,000
Total	8,500	13,200

Table 2. Force structure used for simulation of the Battle of Agincourt.

The model was aggregated in three primary ways:

- The force structures were represented by the greatest common divisor (1 agent representing 100 people).
- Detection and attack were combined into a singular "time to kill" calculation such that enemies in range of each other would schedule a time to kill each other that could only be canceled if one or the other died prior to reaching a scheduled time to kill.
- The terrain was not specifically modeled.

Theories about the battle consider that the French lost through a combination of factors (including a freshly plowed field separating the forces), not the least of which was a lack of respect for massed, aimed fires. The battle was modeled to represent two different COAs based on force deployment options. The first force deployment attempted to describe the historical situation as it was described to have happened. Most notably, the English bowmen were just out of their effective range and the French cavalry began the battle in such a position that they were targeted without the hope of immediate support from the French infantry. This was to simulate a situation where the cavalry was unable to be used as a flanking force. In the first half of Figure 4, the forces to the left represent the massed forces of the French (with range rings prevalent as the range of the French archers) and rightmost forces as the English (note the longer range rings of the flanking wings of long bowmen). The small group of agents separate from the main body represents the French cavalry. The second half of the figure describes the results of the conflict, with smaller dots representing mostly fallen French agents.



Historical Representation

French cavalry are poised to enter the range of the longbowmen with infantry (no flanking).

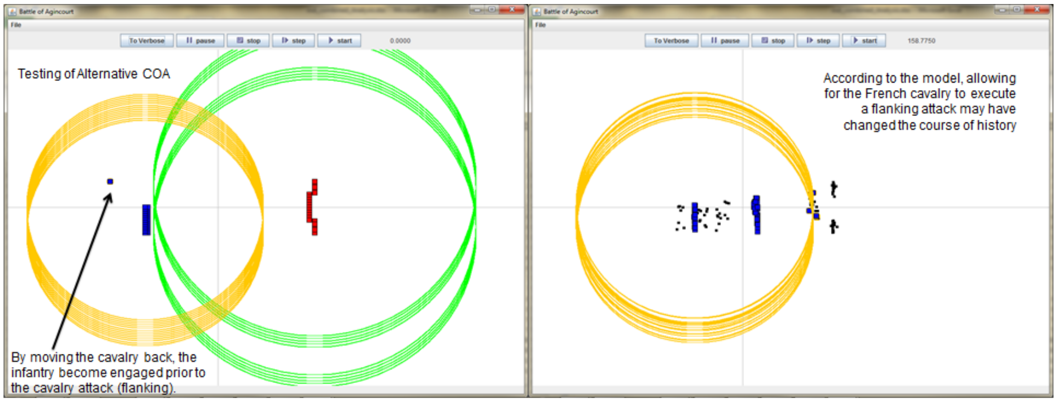
Similar Results as Indicated by History:

Overwhelming English Victory

Figure 4. Representation of the historical force disposition prior to the Battle of Agincourt. The results of the battle (right pane) mimic historical records.

2. Exploration in Development of Alternative Courses of Action

The previous situation was contrasted with that illustrated in Figure 5. The alternative COA in this situation focused on the initial disposition of the cavalry force, which was adjusted to represent a flanking maneuver. In order to represent a flanking behavior, the cavalry was offset from the front lines, allowing the infantry to become decisively engaged prior to cavalry agents crossing into the range of the English archers (yet another abstraction or aggregation in the form of tactical simplification). This action restricted the rate at which the cavalry could be engaged at range, and resulted in quite a different set of results. Though the English occasionally prevailed in this situation, the typical outcome is described in Figure 5.



Testing of Alternative COA

By moving the cavalry back, the infantry become engaged prior to the cavalry attack (flanking).

According to the model, allowing for the French cavalry to execute a flanking attack may have changed the course of history

Figure 5. Testing a modification to the force disposition at the Battle of Agincourt. Had French cavalry been able to flank the English, the result may have been a significant French victory over the English.

The previous scenarios illustrate the value of low-resolution simulation in developing concepts for deeper exploration. Through the use of a relatively simple model, many courses of action could be evaluated. Using a more rigorous, complex model may prohibit extensive problem-space exploration due to increased data collection, run-time, and analysis requirements.

The problem space can be explored using effects rather than the mechanisms for those effects. For example: a combat simulation focusing on survivability could be abstracted to the level of effects. Using a simple model for sensitivity analysis, breakpoints and goals for effects can be determined (i.e. 5% additional sensor range equates to 40% increased survivability). With effects-based goal metrics as a guide, high resolution models can be used to determine how those goals might be achieved (explore the phenomenon). Translating the concept of goal metrics to the previous scenario, the French would have benefited from such an initial low-resolution study. They could have explored a high-resolution model to develop tactics or equipment that would contribute to success against the English, while also recognizing that failure to somehow close the gap between the forces would be catastrophic.

3. Exploration of Increasing Complexity

The same model was reinitialized to perform 20 run batches of a very simplistic version of combat, allowing two equally sized forces of archers to run against one another in a fight to the finish. The English archers held the same advantage from the previous scenario with an effective range of 107% that of the French. In each batch, the number of agents on each side was increased, while the ratio of French to English was held constant/equal. As the agents on each side were completely homogeneous and mimicking aimed-fire, a contrast between this model and the classic Lanchester models could be explored (the assumptions were met). Assuming that this model should behave similar to Lanchester models, the expectation was that time of battle and the percent of English forces surviving would be relatively constant if the ratio of forces was held constant. This was in fact the case that surviving English forces (Figure 6) and battle duration were similar, though there was variation in the surviving English forces.

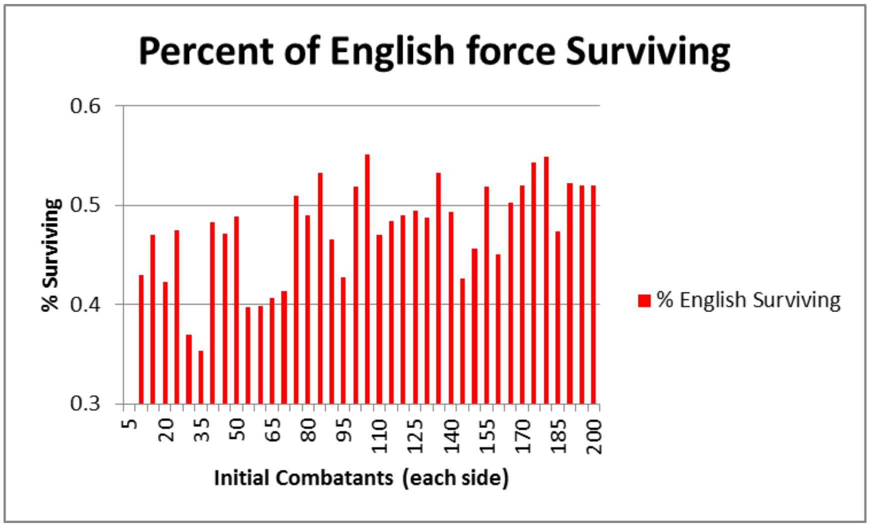


Figure 6. Battle survivors were statistically similar, as with Lanchester models

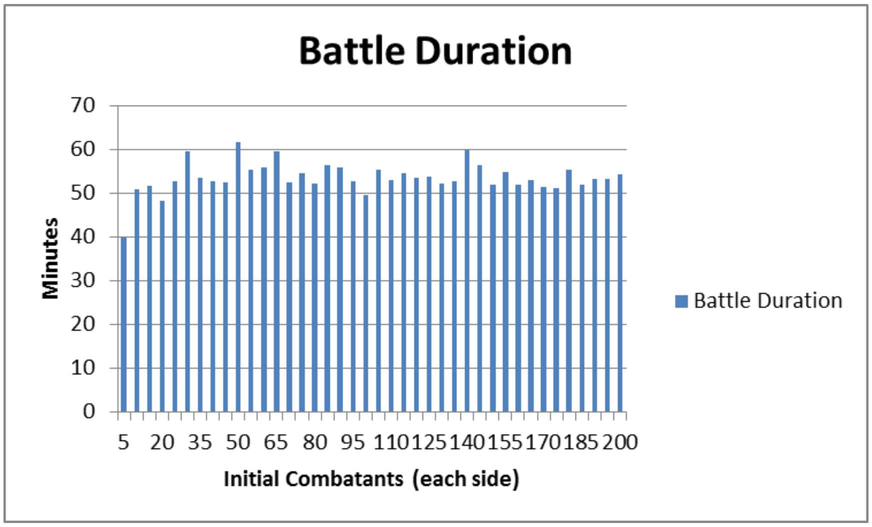


Figure 7. Duration of combat was statistically similar, as with Lanchester models.

More interesting was the processing time (as measured by system clock time) associated with arbitrarily increasing the model complexity (higher resolution) by increasing the number of agents modeled. As more agents were added with a constant ratio between both competing sides, the system load increased and processing time went up. Though the trend followed a polynomial rate of increase initially, higher numbers of entities exceeded the prediciton significantly (predicted processing time of 321 seconds for 1000 agents on each side, actual time of 1,324 seconds).

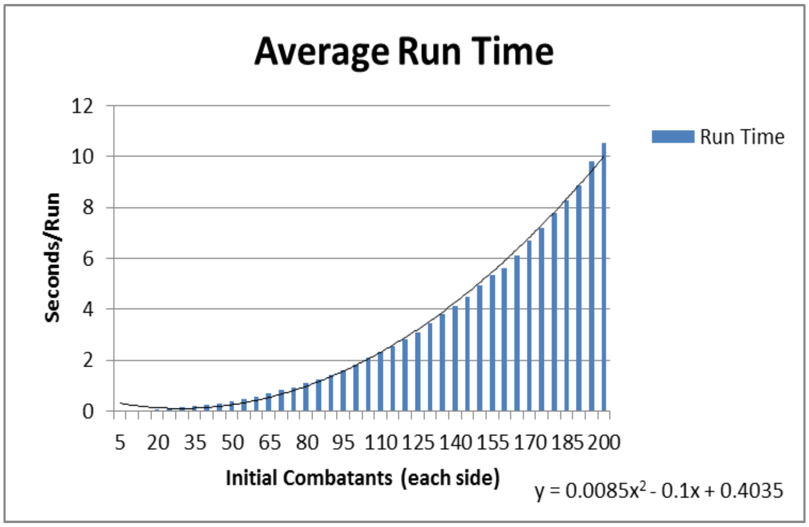


Figure 8. Model run time as a factor of agent count.

This was done to explore the concept that more detailed, complex models are not necessarily more accurate when assessing metrics that could be associated with a lower resolution model; specifically that increasing details does not necessarily affect results. It may seem overly simplistic to contrast such a measure of complexity, but models often include factors that do not affect the metrics being measured. As agents are enriched with more properties to better reflect reality, they become more complex (and thereby increase the complexity of the simulation). As additional control measures and additonal potential interactions and triggers are added, complexity also increases. In the previous example, the net effect was merely longer processing times for the same results.

Extrapolating these results to a real-world complex modeling situation, the addition of additional properties, interactions, and agents increases complexity quickly. Optimally, only relevant factors and agents would be represented in a model. That is almost never the case:

- Many models provide a schema for scenario creation and innate behaviors that must be addressed entirely (all the blanks must be filled in). In allowing for a spectrum of behaviors, the mechanisms for those behaviors need to be addressed, even when not utilized.
- Determining which agents and interactions "matter" is not necessarily easy or obvious. This lack of knowledge may be the purpose of the model.
- Though reusability is a valuable property in a model, artifacts from previous renditions may be present and difficult to remove, while still increasing model complexity.

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IV. METHODOLOGY

This section discusses the methodology used to implement the COMBATXXI scenario in DAFS for comparison through experiment.

A. MODEL DEVELOPMENT

The initial intent of this research was to contrast the development, execution, and results of a DAFS model built to mirror a current study being conducted through either WSMR or MCCDC using COMBATXXI. As a step toward this long-term goal, this study was conducted with consideration to limitations based on information classification restrictions, scenario complexity, and the process of developing relational parameters. A COMBATXXI scenario developed by MCCDC proved to be most amenable to the application of simplified analysis and the testing of comparable metrics. In particular, a portion of the Phase 0 of one of the scenarios used as part of the ACV AOA was explored.

1. Scenario Description

The MCCDC COMBATXXI scenario described a reinforced Marine rifle company (as a portion of a MEU) coming ashore in the general location of MCB Camp Pendleton, California. From there, the company was set to embark on ACVs and travel south along the coast to eventually move inland through an urban area. The scenario was designed to thoroughly represent the facets of an amphibious landing on a foreign shore, including communication networks, entrenched enemy forces, numerous different combat platforms including aviation assets, and 5 meter resolution terrain (pictured in Figure 9 without terrain overlay to enhance visibility of unit control measures).

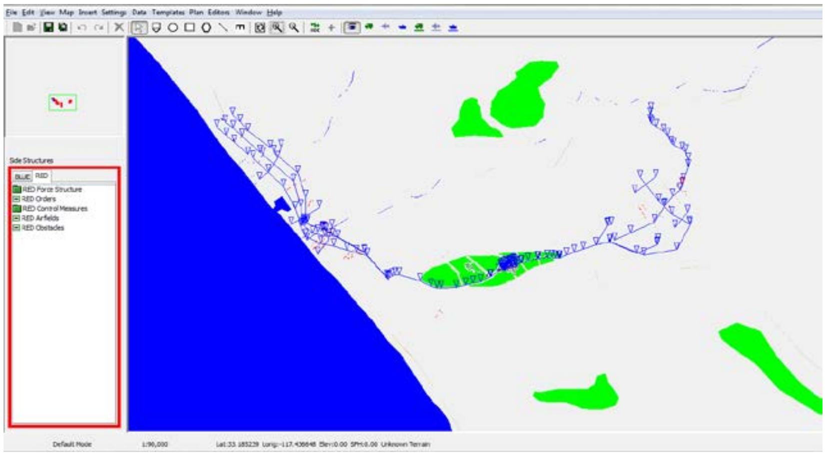

File Edit View Map Insert Settings Data Templates Plan Editors Window Help
Side Structures
BLUE
RED
RED Force Structure
RED Orders
RED Control Measures
RED Airfields
RED Obstacles
Default Mode
1:90,000
Lat:33.185239 Long:-117.438648 Elev:0.00 SPH:0.00 Unknown Terrain

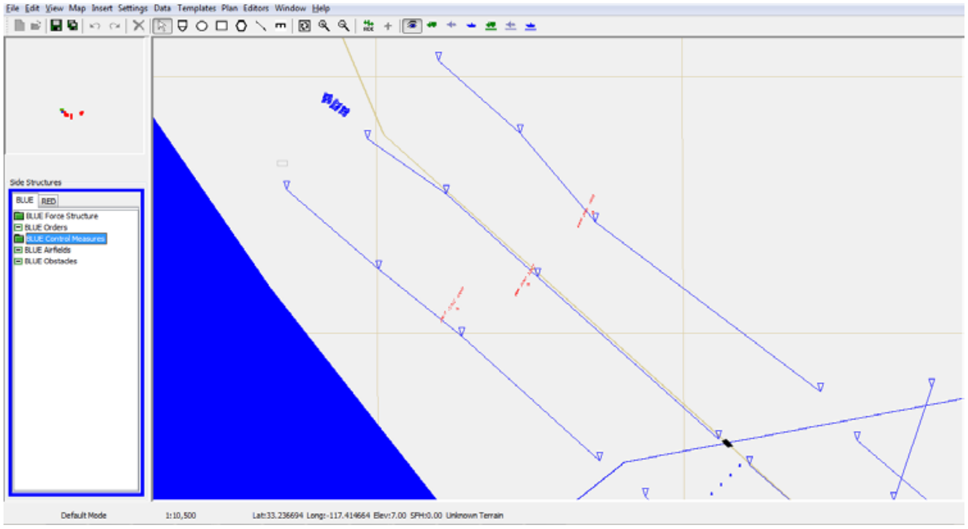
Figure 9. COMBATXXI preprocessor view of ACV Phase 0.

In partnership with Major Chris Fitzpatrick, a MCCDC simulation developer and analyst whom had worked intimately with the original scenario creation, the scenario was modified slightly to enhance compatibility with DAFS. In the original form and in conjunction with the purpose of the study, the units came into contact with enemy forces while aboard the proposed model of the ACV. Major Fitzpatrick was able to modify the behaviors such that the ground forces moved southward dismounted, which made the conflict between the Marines and enemy forces more dynamic and somewhat less favorable for the Marine entities.

2. Scoping the Scenario

One vignette of the larger MCCDC Phase 0 was modeled in DAFS as an example of how this methodology might be implemented on a larger scale. In contrast with the purpose of the COMBATXXI scenario, the DAFS scenario was developed as a prototype representing the initial conflict between friendly and enemy forces. As the COMBATXXI model can be stopped at arbitrary points, it was set to conclude data collection after a reasonably short portion of execution. This allowed for more expeditious data collection and simplified analysis in both models. Over the course of a route composed of four waypoints (approximately 2 km), the Marine unit was designed to come into direct contact with an enemy rifle company.

Artifacts of the original design are still present in the focus vignette (i.e. the ACVs, three routes, many units not pictured here, etc.). Though removing other aspects not related to both models would make for a more even comparison in execution times, many of the behaviors associated with entities in COMBATXXI are tightly coupled; removal of seemingly non-essential entities may cause systemic problems due to referenced hierarchies in command structures and behaviors. Though only the rightmost route is used by the COMBATXXI model agents, the remaining two routes allowed for a rapid AOA in tactics based on changes in routing with the DAFS model by using the other two pictured routes as alternatives. In Figure 10, dismounted infantry has not yet begun their movement toward the first waypoint (top right inverted triangle).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BLUE Orders
BLUE Control Measures
BLUE Airfields
BLUE Obstacles
Default Mode
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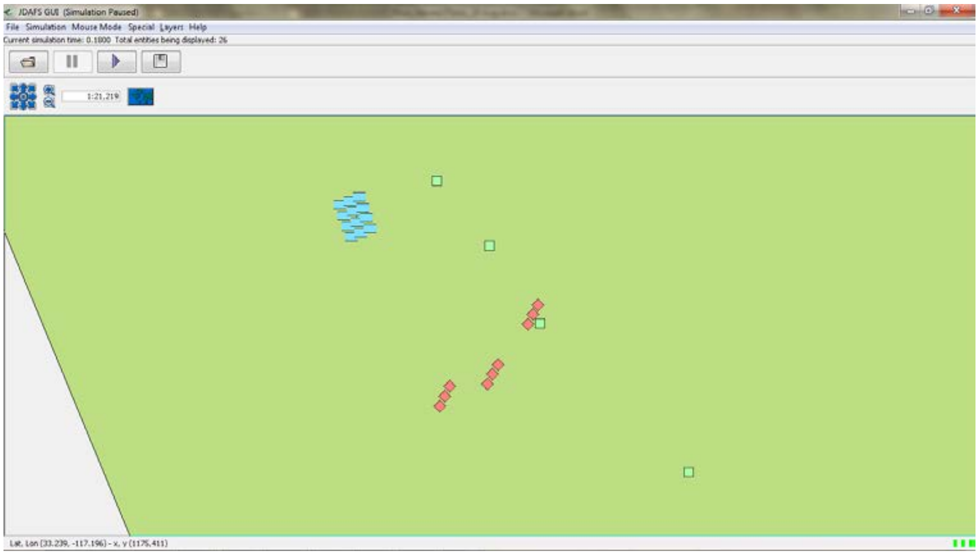
Lat:33.236694 Long:-117.414664 Elev:7.00 SFH:0.00 Unknown Terrain

Figure 10. Unit disposition in COMBATXXI scenario.

The DAFS model does not explicitly display waypoints through the GUI, so points were added as visual control measures for comparison (green squares). Three different scenarios were developed in DAFS to represent three different alternatives. In the COMBATXXI scenario, the Marine agents move via waypoints represented by the blue line with inverted triangles representing waypoints along the easternmost (rightmost) route (Figure 10). By referencing the COMBATXXI scenario, three different DAFS scenarios were created corresponding the the three distinct routes portrayed in the

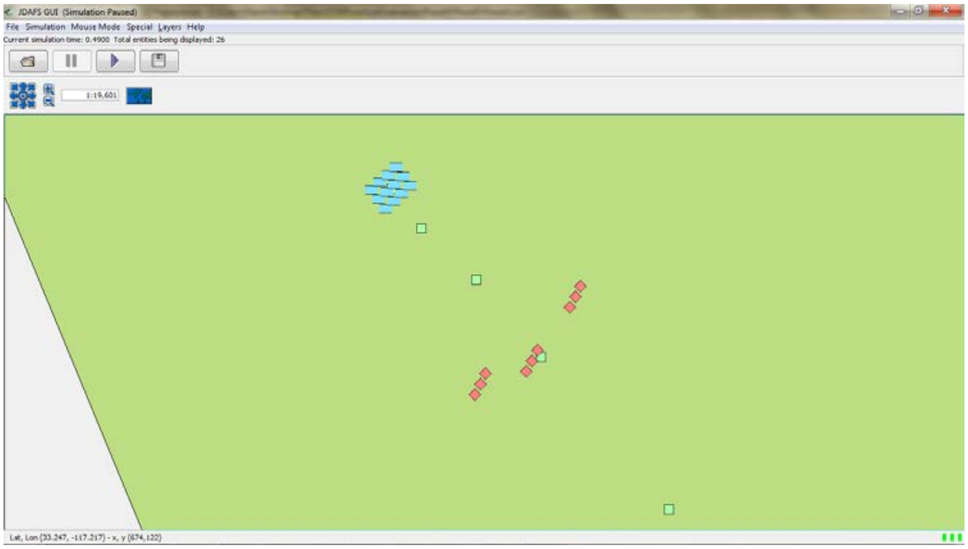
COMBATXXI scenario. The first DAFS scenario corresponds to the COMBATXXI scenario, while the other two are variants represent the central and westernmost routes respectively.


JDAFS GUI (Simulation Paused)
File Simulation Mouse Mode Special Layers Help
1:21,219

Current simulation time: 0.1800 Total entities being displayed: 26

Lat, Lon (33.239, -117.196) - x, y (1175,411)

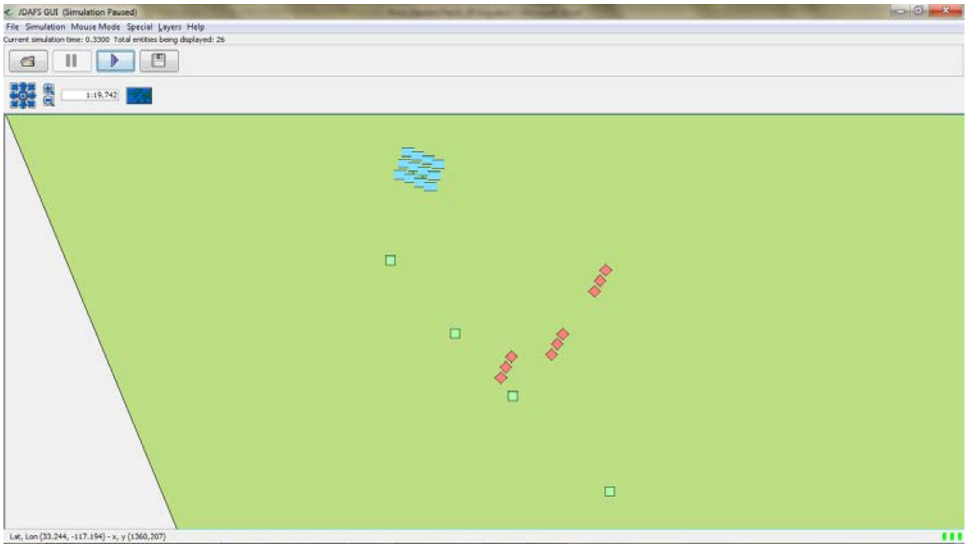
Figure 11. DAFS scenario translation (eastern route).


JDAFS GUI (Simulation Paused)
File Simulation Mouse Mode Special Layers Help
1:19,601

Current simulation time: 0.4900 Total entities being displayed: 26

Lat, Lon (33.247, -117.217) - x, y (674,122)

Figure 12. DAFS scenario translation, variant 1 (central route).


JDAFS GUI (Simulation Paused)
File Simulation Mouse Mode Special Layers Help
1:19,742

Current simulation time: 0.3300 Total entities being displayed: 26

Lat, Lon (33.244, -117.194) - x, y (1360,207)

Figure 13. DAFS scenario translation, variant 2 (western route).

3. Performance Measures and Metrics

Two disparate research questions were addressed: determine the utility of DAFS as a prototyping model for complex simulations and assess ability to provide a rapid assessment of sufficient quality with low-resolution inputs. A variety of metrics were measured in experimentation.

Performance Measure	Metric	Method of Measurement
Ease of Use	Objective Opinion	Personal Estimate
Validity of Results	Total Time Of Battle (active fighting from first shot to last shot)	Simulation Log Files
	Survivors	Simulation Log Files
	Detection – distance	Simulation Log Files
	Detection – time	Simulation Log Files
Computational Demands	System Run Time	Simulation Log Files

Table 3. Performance metrics.

B. MODEL PARAMETER ESTIMATION AND TRANSLATION

In order to create a scenario similar to the one provided from MCCDC, it was necessary to translate the COMBATXXI model parameters into DAFS. This posed some challenges. COMBATXXI focuses on modeling scenarios by describing details such as terrain, logistics, communications, complex target acquisition, etc. Many of these details are not specifically modeled in DAFS. In order to do so, the DAFS construct would need to be made as complex as that of COMBATXXI. Though DAFS can be modified to enrich scenarios, modifying it to the point that it accepted all of the details available in the COMBATXXI scenario would be counter-productive and eliminate any of the potential value inherit in DAFS simplicity.

It was necessary to abstract some parameters in order to develop a model in the DAFS framework. In an effort to make the data simple, keep the run times low, and reduce the effort to analyze the results, some fidelity is lost in the translation process. In the following section, the data was translated to represent the effects present in COMBATXXI closely, but not exactly. The research question of this thesis probes the efficacy of the techniques attempted here.

1. Aggregation Translation

One such modification was unit aggregation. In COMBATXXI, each entity was uniquely represented by an individual simulated agent. By contrast, the choice was made to represent multiple entities per agent in DAFS. Generally, each squad (group of approximately 11–13 plus commanders) was counted as a single agent in DAFS. For example, an enemy platoon is represented in COMBATXXI by 34 individual agents. In the DAFS version of that same unit, it was represented by 3 agents. There were 287 discrete agents represented in COMBATXXI. The 185 agents of the reinforced rifle company were represented with 12 aggregate agents in DAFS while the 102 enemy agents were represented by 9 aggregate agents. Therefore the model was scaled to an approximate agent representation of 13.7 to 1.

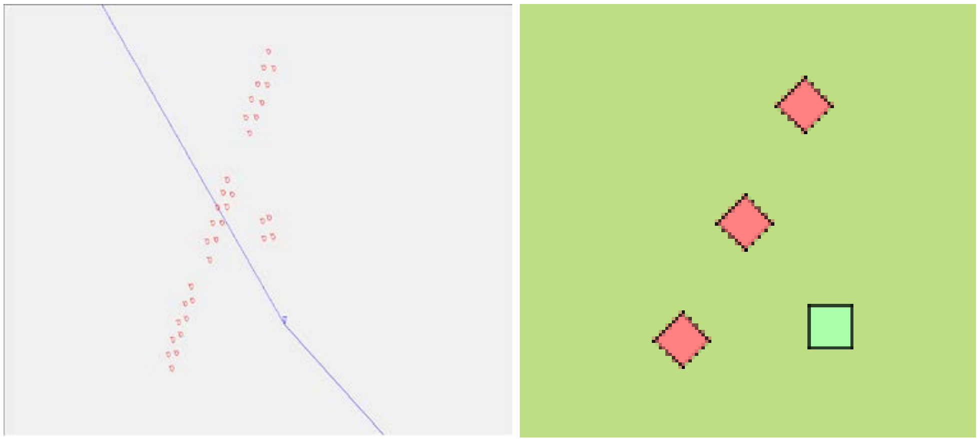


Figure 14. COMBATXXI and DAFS representation of the same units. The inverted triangle on the left and the green square on the right represent the same waypoint.

Though the threat units were armed rather simply with small arms (AK-47), the Marine units were augmented with heavy weapons in the form of 60mm mortars and JAVELIN missiles. The mortars were not directed against the enemy units in this portion of the scenario. The JAVELIN missiles are an anti-armor weapon, but were employed in this scenario as an anti-personnel weapon and were subsequently represented as such in DAFS. The Marine individual weapons were the XM-29 assault rifle variant with 5.56 mm standard rounds plus programmable, air-burst munitions and the M-249 Squad Automatic Weapon (SAW).

2. Position Translation

Though DAFS uses OpenMap in conjunction with the GUI, the model represents its entities locally over a flat earth. These local coordinates are correlated to latitudes and longitudes, but at an increasing error as they project from the center of the model focus point. DAFS performs well without specific relation to latitude and longitude, relying on distance in meters in relation to the other agents of the simulation. As terrain is not modeled in DAFS, a simulation can be run anywhere without regards to global location, and have similar results. In order to model the COMBATXXI as closely as possible, the map was re-centered (the relational center was moved), and each point was translated by linear forecast related to a test case of five points. The test case error was insignificant with regards to the y-axis (latitude), as lines of latitude are evenly spaced. At the extreme edges of the test case (10,000 meters from the center), the translation error was less than 14 meters in longitude.

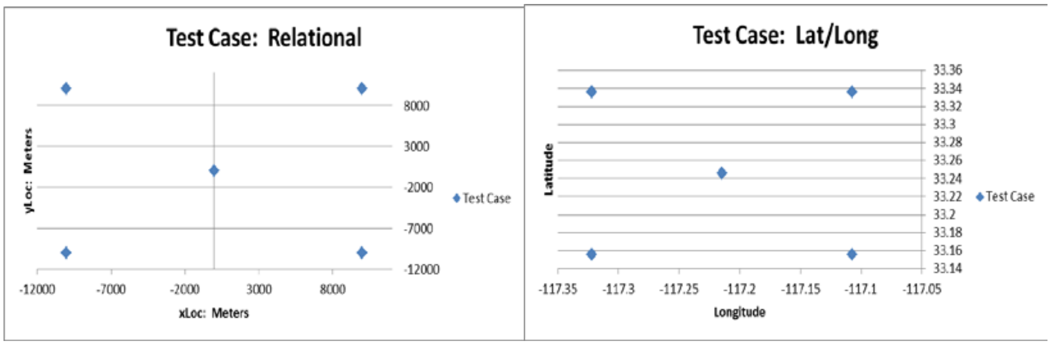


Figure 15. Relational test case translated to latitude and longitude.

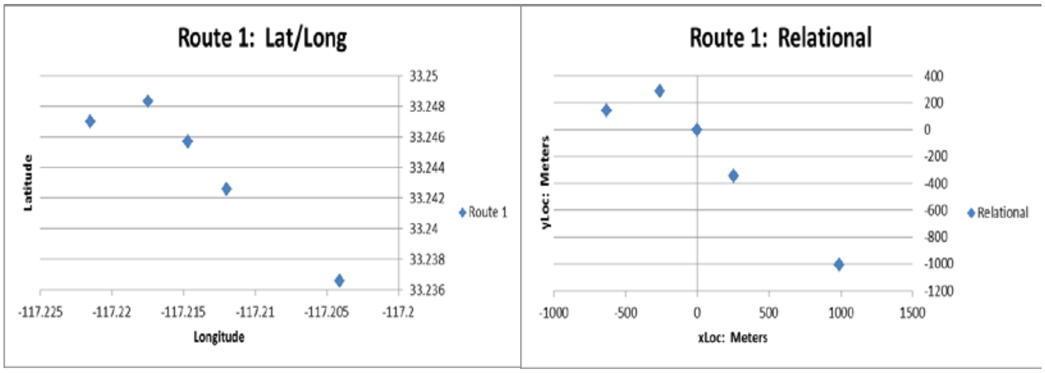


Figure 16. Route 1 coordinates translated to relational coordinates.

Waypoint	Long	DAFS xLoc	Lat	DAFS yLoc
Start	-117.2215	-633.44078	33.247	144.124169
wp1_Route 1	-117.2175	-260.82855	33.2483	288.248337
wp2_Route 1	-117.2147	0	33.2457	0
wp3_Route 1	-117.212	251.513249	33.2426	-343.68071
wp4_Route 1	-117.2041	987.422385	33.2366	-1008.8692
wp1_Route 2	-117.2200	-496.5327	33.2455	-20.662762
wp2_Route 2	-117.2173	-239.9399	33.2436	-236.1254
wp3_Route 2	-117.2141	59.4183	33.2407	-558.47108
wp4_Route 2	-117.2077	651.0072	33.2350	-1189.59
wp1_Route 3	-117.2229	-762.4461	33.2437	-218.37681
wp2_Route 3	-117.2196	-460.6755	33.2409	-527.80256
wp3_Route 3	-117.2167	-189.8276	33.2386	-788.02819
wp4_Route 3	-117.2119	262.7187	33.2342	-1273.5043

Table 4. Translation of locations.

3. Movement Speed Translation

Unit movement speeds for DAFS units were based on observed speeds for units in COMBATXXI. The average speed of the infantry units to complete the scenario was 179.8 meters per minute, with a maximum speed of 201 meters per minute. The DAFS units were attributed the maximum speed of 201 m/min, as the parameter in DAFS is referred to only as the maximum speed.

4. Sensor Translation

COMBATXXI sensors relate the detection of a target to a stepwise conceptual model. In COMBATXXI, a target goes through levels of acquisition. At each level of acquisition, more information is determined about the target until enough information is available to the sensing agent to make an appropriate action decision. Targets may be acquired multiple times per agent. The agents in this scenario were not eligible to attack enemy units until a level of acquisition of identification had been achieved. Achieving acquisition is based on many scenario parameters such as line-of-sight calculations (including entity orientation/heading), agent observing, agent being observed, field of view, etc. In order of representative fidelity of the sensor in question, the levels of acquisition are as follows:

- Detection: ground, air, or sea entity or life form
- Classification: basic type of entity (i.e. human, wheeled vehicle, rotary wing aircraft)
- Recognition: general category of entity (i.e. attack helicopter, tank, military personnel)
- Identification: specific description (enemy T72, friendly UH-60)

The detection algorithm for COMBATXXI is potentially very complex (depending on how the scenario was developed and what features have been activated) and relatively computationally intense. The DAFS approach to determining detection involves estimating a time until detection. An enemy agent is assigned a time to detect once it enters the range of an active sensor. If that agent leaves the range of the sensor before detection, it is not detected. Once an agent is detected, it remains detected until it exits the maximum range of the sensor platform. As DAFS does not represent terrain, it does not explicitly model line-of-sight.

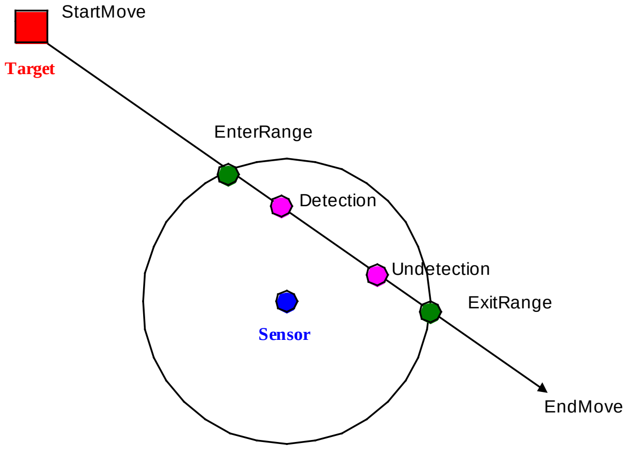


Figure 17. DAFS sensing methodology (from DAFS User Guide, September 2012).

As the COMBATXXI scenario is part of a larger study, the data provided in the observer log following a simulation run included the detections of units outside of the scope of the focus area. The COMBATXXI data included data on all four levels of acquisition. With these points in mind, the data in the COMBATXXI logging file was sorted by distance to the target area as well as by the identification acquisition level, decreasing the number of detections to be analyzed from 691,743 to 81,237. The human eye sensing data related a relatively exponentially distributed rate of detections throughout the 13 minutes of simulation time required to run the scenario. The binocular sensing data revealed some interesting peaks as part of the distribution, as well as the fact that binoculars did not involve a detection level of acquisition. Within the secondary peak of the data, 20517 of the 27309 binocular identification acquisitions occurred (more than 25% of the total of both sensors).

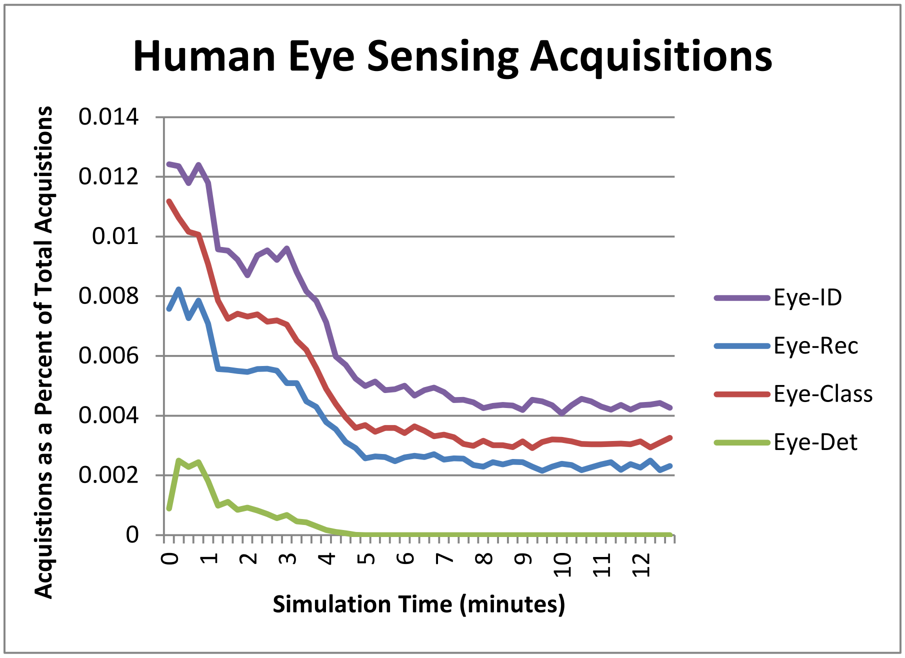


Figure 18. Human eye sensing acquisitions by acquisition levels from 5 sample COMBATXXI scenario runs.

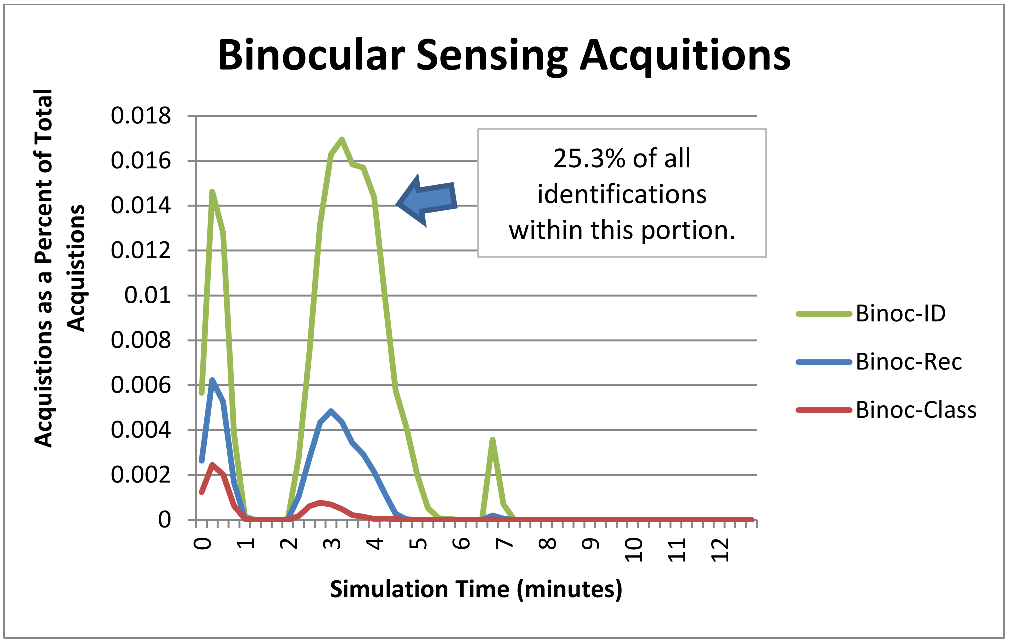


Figure 19. Binocular sensing acquisitions from 5 sample COMBATXXI scenario runs. Note the concentrated area of identifications.

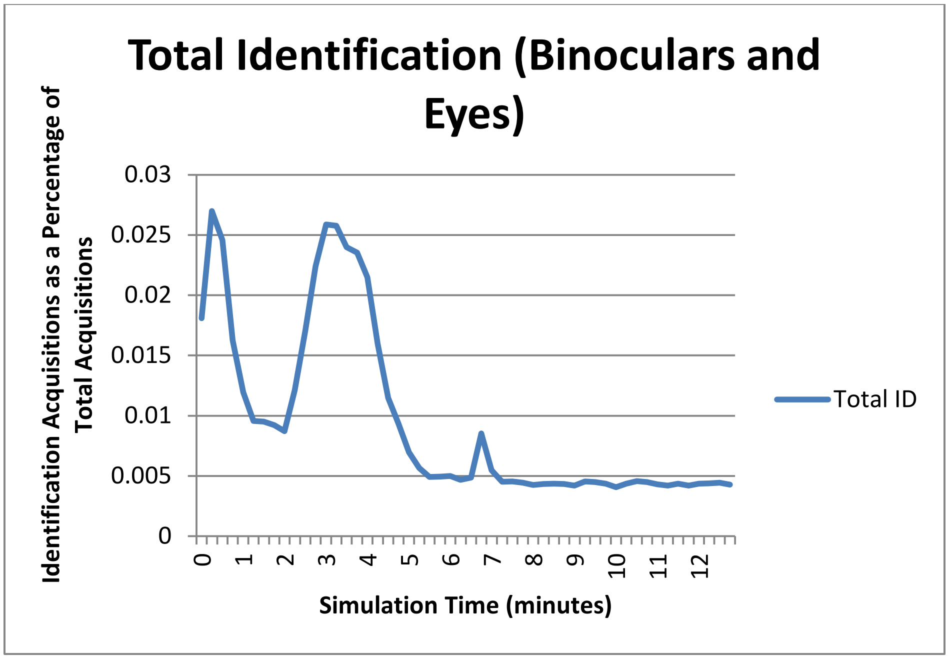


Figure 20. Total relative identification level acquisitions from 5 sample COMBATXXI scenario runs.

Once a sensor in DAFS registers detection, it is approximately equivalent to the same agent achieving the identification acquisition level in COMBATXXI. The DAFS agent can immediately engage enemy targets upon detection. A simplistic method of representing detection is through the comparison of random number draws to a distribution of sensor detections. In DAFS, a combination of distributions was used to represent the detection of enemy agents. Five of the COMBATXXI experimental runs were analyzed. A distribution was built based approximate relation of human eyes and binoculars sensing in the COMBATXXI scenarios.

Initially, an attempt was made to mirror the cognitive process of sensor acquisition in DAFS similar to the process described in COMBATXXI. The COMBATXXI output files provided times to detect related to each level of acquisition. It seemed that a combined distribution of exponentially distributed rates of detection would be representative, but in practice the results did not nearly reflect the results of sensing in COMBATXXI. Other aspects of the COMBATXXI acquire algorithm apparently contributed to detection time in a ways that were not explored. Alternatively, the rate at which agents achieved an acquisition level of identification in COMBATXXI was used to develop the DAFS model.

In order to represent the identification phenomenon from COMBATXXI in DAFS associated with human eyes, a probability distribution was fit to approximate the rate of detections. The sensor distribution associated with human eyes was aproximate to that of an exponential distribution with the same mean value of the identification acquisition level derived from the COMBATXXI scenarios (5.13 minutes). When contrasted with the actual data, it is obvious this is a rough approximation.

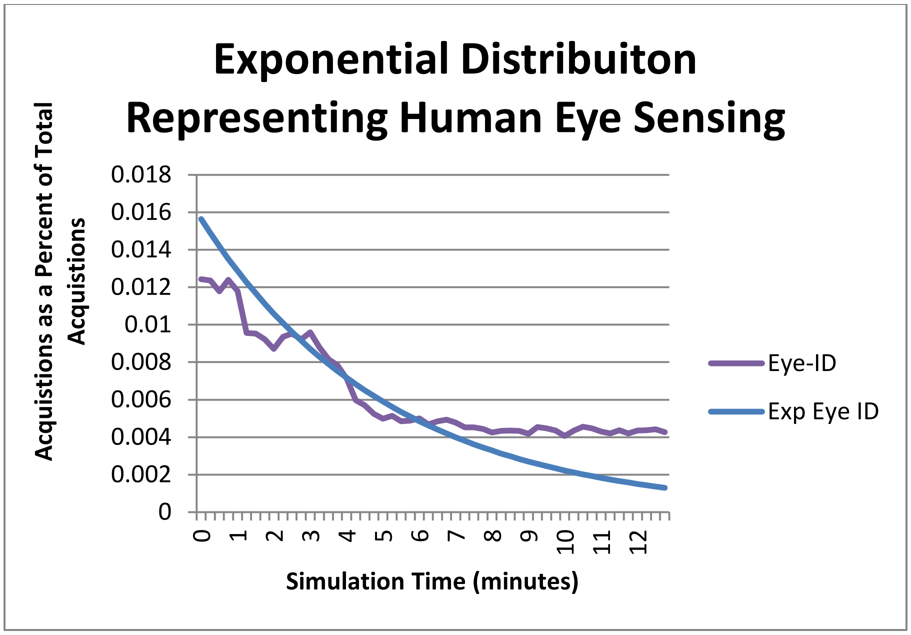


Figure 21. Contrasting an exponential distribution with the actual distribution of human eye identifications.

Similarly, a distribution was fit to the data representing the binocular identifications in the COMBATXXI scenarios. The actual data was separate as discrete peaks through the simulation time. Initially a normal distribution was applied to capture the majority of the identifications located in the second peak of the actual distribution. This normal distribution was based on the mean (3.64 minutes) and standard deviation (.648) of only those identification acquisitions from the COMBATXXI scenario found within that region and disregarding the identifications without. As the normal distribution could allow for negative values at extreme deviations from the mean, it was approximated with a gamma approximation of the normal where Gamma (α,β) is represented with $\alpha = \mu^2/\theta^2$ and $\beta = \theta^2/ \mu$.

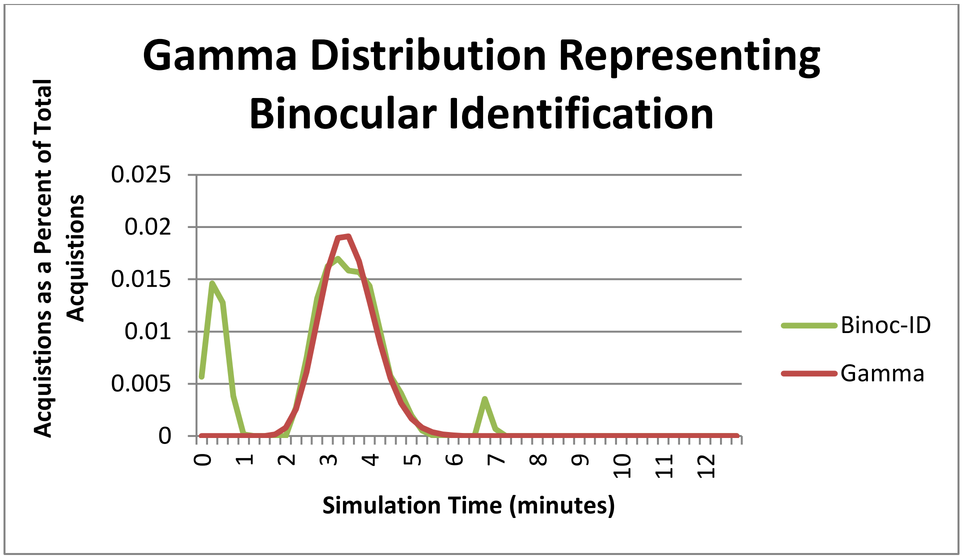


Figure 22. Contrasting a gamma distribution with the actual distribution of binocular identifications.

When the two distributions were combined, the approximation of the identification sensing parameter was complete. DAFS allows for one platform to maintain more than one sensor. By attaching two sensors with different capabilities to one platform, two detections are possible. The first DAFS detection allows the entities to interact (attack) if within range of an equipped weapon. The combined sensing distributions were thus represented in the translation of the COMBATXXI scenario.

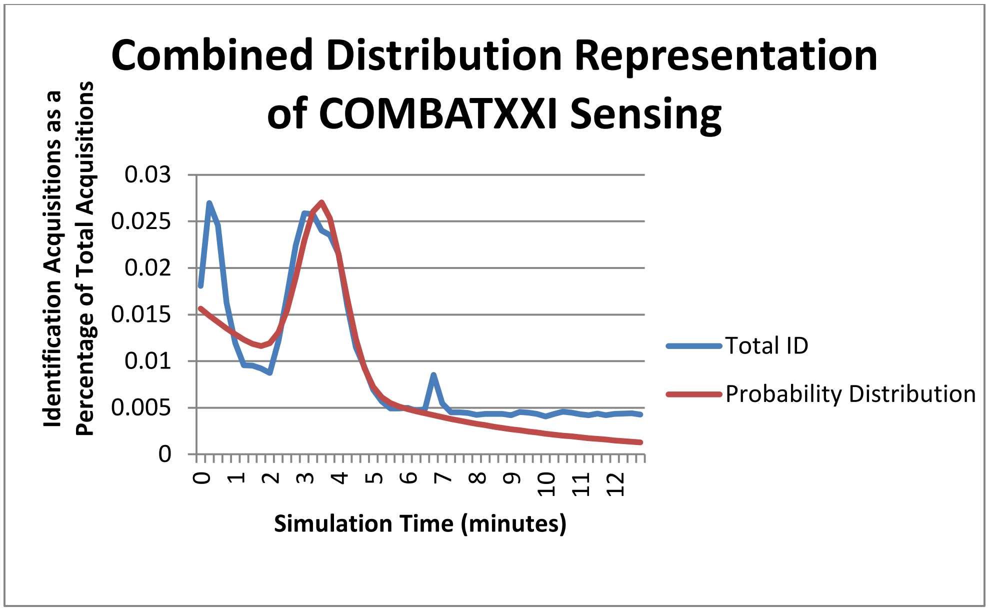


Figure 23. Contrasting the combined gamma binocular approximation and exponential human eye approximation with the actual COMBATXXI distribution.

This technique of mimicking distributions worked sufficiently well in this scenario and under these starting conditions, namely that all units were within sensor range. To apply these techniques to a more general case involving initial entry into sensor ranges by searching entities may require an entirely different approach. Unfortunately, this analysis is well beyond the scope of this study.

5. Weapon Capabilities Translation

COMBATXXI develops situation probabilities to hit (P_{hit}) and probabilities to kill (P_{kill}) based on weapon capability, range, and other environmental variables. First, a weapon must hit the target in order to do any damage. Once a hit is determined, then damage is assessed. COMBATXXI assess damage systemically. This can lead to a complex set of possible conditions for the target of weapon effects such as target suppression, partial damage and capability kills (mobility, communications, firepower, etc.).

DAFS describes weapon effects differently. One schema available when developing a DAFS scenario involves using a linear P_{kill} that equates to the possibility of a killing a target given some portion of time to shoot at that target linearly distributed between the minimum range and maximum range P_{kill} values. The portion of time is derived from the frequency with which DAFS is set to re-evaluate the local optimal firing solutions for targets through the CVO. As weapons capabilities are given in rounds per minute, a convenient setting for the DAFS CVO evaluation periods was .1 or 1/10th of a minute or 6 seconds. By deriving the chance for each round to both hit and kill a target for each weapon-target mix and calculating the probability of a kill per 6 second time period (by subtracting the probability of missing every shot in that time period from 100%) based on weapon fire rates and reload times, the DAFS model weapons capabilities were able to be populated.

The weapons capabilities were translated from unclassified weapons data provided from MCCDC (T. Roofner, personal communication, 14 September 2012). The data provided included accuracy data based on the standard deviations in angular error for the associated weapon system given in mils. By converting the angular deviation to relative miss distance, 10,000 Monte Carlo normally distributed random draws individually multiplied by the deviation per mil divided by 1000 provided the average P_{hit} for the associated weapon system based on meters. The entities of the simulation remained in the standing position in both the COMBATXXI and DAFS scenarios. If the relative miss distance was less than half of the presented area of a standing target, that draw indicated a hit. The linear P_{kill} for each weapon per round of ammunition was determined by multiplying the P_{kill} times the P_{hit}. Minimum range P_{hit} for weapons with no effective minimum range was assessed to have 100% chance to hit their intended target at a range of 0 meters.

	Min Range	Max Range	Min Range P-kill	Max Range P-kill	P-hit (Max Rng)	Lin P - Kill per Round (Max Rng)
AK-47---7.62/ps	0	400	0.7	0.525	0.0844	0.04431
M249---M855	0	1000	0.7	0.121	0.0058	0.0007018
XM29---XM1018	100	500	.32 @100m*	.12 @500m*	*	*
FGM148---JAVELIN	65	2500	0.99 @65m*	0.66 @2500m*	*	*

Table 5. Weapons effectiveness data for DAFS scenario (from T. Roofner, personal communication, 14 September 2012). * The XM29 and FGM148 data provided were already in the format of probability to hit and kill a target

These linear P_{kill} rates were then translated from linear P_{kill} per round to linear P_{kill} per 6 second time period. Based on the MCCDC data, reload times were available. A few assumptions were made concerning ammunition and reloading:

- 30 round magazines for AK-47
- 100 round magazines for M-249
- 6 round magazines for XM-29
- As the XM-29 airburst munitions is meant, in part, to replace the M-203 grenade launcher and unclassified weapons data is not yet available, the rate of fire for the XM-29 was assumed to be the same rate of fire for the M-203 (5-7 rounds per minute).
- P-kill was scaled based on the proportion of weapon types available (i.e. only 1/4th of the Marines in a fire team are equipped with a M249).

- P-kill was scaled based on the assumption that not every Marine or enemy soldier would be using their weapon to the maximum extent possible; some proportion were assumed to be moving or communicating. The amount of total rounds fired per agent was reduced by 1/5th in order to represent this phenomenon.

	Sustained Rate of Fire (rpm)	Reload Time (seconds)	Min Range P-kill per 6 seconds	Max Range P-kill Per 6 seconds	Scaled Min P-kill per DAFS agent	Scaled Max P-kill per DAFS agent
AK-47---7.62/ps	400	10	~1.0	0.429	~1.0	0.3614 @ 4/5th
M249---M855	50	30	0.9919	0.0032	0.6183	0.0006 @ 1/5th
XM29---XM1018	6	30	0.2066	0.0738	0.1296	0.04498 @ 3/5th
FGM148---JAVELIN	n/a	n/a	0.99*	0.66*	0.066	0.044 @ 1/15th

Table 6. Linear P_{kill} per time unit (6 seconds) incorporating reload times and assumptions. P_{hit} for min range is assumed to be 100% (excepting FGM-148, which was estimated for a single shot).

Although most weapons were equitably distributed throughout each squad in the company, there were only two JAVELIN missile operators as part of the reinforcing assault force for the Marine unit represented in COMBATXXI. Though the JAVELIN is an anti-armor weapon, it was fired against enemy infantry units in the simulation runs in COMBATXXI. The fact that this is not a logical tactic is inconsequential to this study. Because it was represented in the COMBATXXI scenario, it needed to be represented in some manner in DAFS. One aggregate unit was assigned a JAVELIN weapon capability in addition to their other capabilities, but was prevented from making any more than two shots per simulation run.

C. ASSUMPTIONS

In order to abstract the situation from a higher resolution model to a lower resolution model, several simplifying general assumptions were made.

- Agents of similar units have similar strengths and weaknesses.
- Aggregate agents of units can be ascribed the same fate with reference to movement and attrition as the rest of the agents within their aggregate unit (i.e. if a fire team dies, all members are assessed as deceased).
- Units are either fully capable or dead/completely incapable. The concept of mobility kills or firepower kills is not addressed in DAFS.
- Terrain, though relevant in real life and COMBATXXI, is irrelevant in DAFS. Shifting the locations was acceptable.
- The most significant assumption was that unit aggregation, position errors, movement speed differentials, differentials in the sensor distributions, and approximations of weapons effects will still provide similar results in the low-resolution model as in the high-resolution model.

D. DESIGN OF EXPERIMENT

The experimental design was relatively simple and straight-forward. All runs were made on the same desktop computer (i2600k processor, 16 GB RAM, Windows 7 OS, all background processes minimized). Twenty runs were completed in COMBATXXI terminating upon completion of the route waypoints in batch mode to reduce processor workload. Two hundred batch runs were completed of each of the three separate DAFS scenarios. Log files and execution times were stored for later comparative analysis.

V. RESULTS

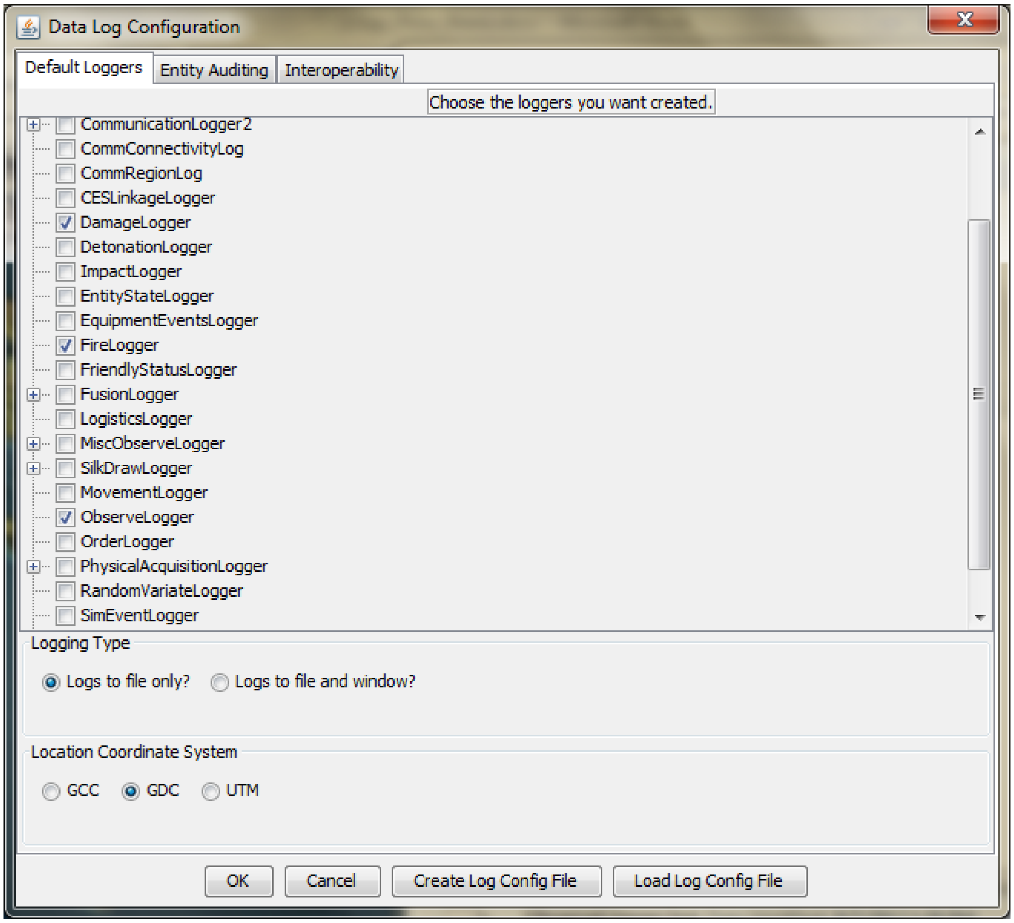
The COMBATXXI and DAFS scenarios results were contrasted. As the first 5 COMBATXXI runs were used to calibrate the DAFS model, the only aspect of these runs used in the final analysis was the computational time requirements necessary to complete those runs. Ten of the remaining COMBATXXI runs were used to generate the performance metrics used in comparison. The DAFS scenario was run on three different routes, the first of which followed the same route as that used in the COMBATXXI scenario. The remaining two batches followed alternate routes to the same objective. The first DAFS scenario was used to contrast the bulk of the performance metrics, as it most closely resembled the COMBATXXI scenario it was built to resemble.

A. OBJECTIVE OPINION

In experimenting with both models, there were many apparent differences, for which system usability metrics were not assigned. Though some basic precepts are similar, in execution the models had very different interfaces and outputs.

1. Ease of Use: COMBATXXI

COMBATXXI is a complex model, not just in the interactions between the agents, but also regarding output. As this study focused on a pre-existing scenario for contrast, much of the effort involved in development was transparent to this study. There are several output options in the form of optional log files. Different log files provided reporting on different aspects of the scenario and the associated interactions



Choose the loggers you want created.

□ CommunicationLogger2
□ CommConnectivityLog
□ CommRegionLog
□ CESLinkageLogger
☑ DamageLogger
□ DetonationLogger
□ ImpactLogger
□ EntityStateLogger
□ EquipmentEventsLogger
☑ FireLogger
□ FriendlyStatusLogger
□ FusionLogger
□ LogisticsLogger
□ MiscObserveLogger
□ SilkDrawLogger
□ MovementLogger
☑ ObserveLogger
□ OrderLogger
□ PhysicalAcquisitionLogger
□ RandomVariateLogger
□ SimEventLogger

Logging Type

● Logs to file only? ○ Logs to file and window?

Location Coordinate System

○ GCC ● GDC ○ UTM

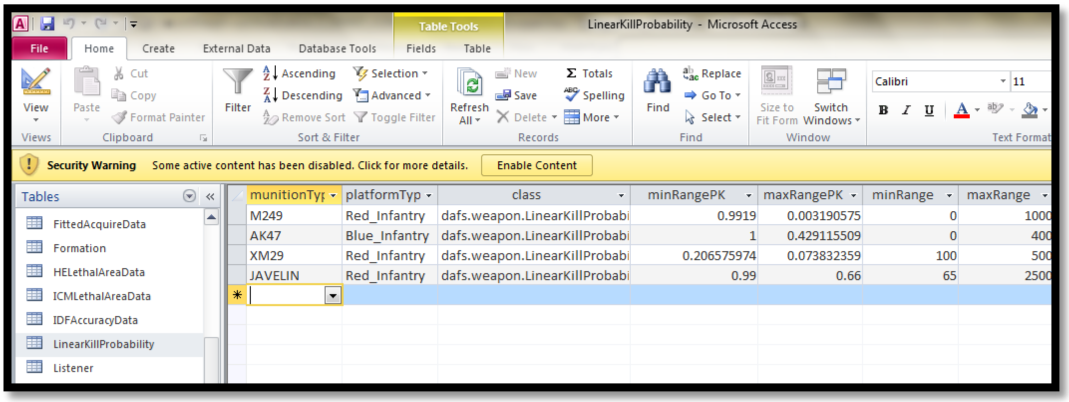
Figure 24. Sample of options associated with log file creation. Those log files selected were those used in the final analysis.

The log files in COMBATXXI can be quite thorough and extensive. High-resolution models can capture high-resolution output in order to enable the exploration of the intricacies of the many possible interactions represented therein. The input variables for complex algorithms are available and traceable. Some of the logs were larger and more complex than others. In this scenario as one of the extreme examples, the ObserverLogger for a single run representing 13 minutes of real-time included between 130,000 to 150,000 rows of 33 columns of data (approximately 4.5 million data points). Not all of fields are used based on scenario settings, and most log files are smaller than the ObserverLogger. The sheer volume of data was immense. For 20 runs of this minimal scenario, the COMBATXXI log files were 835 MB (including ObserverLogger, FireLogger, and DamageLogger as well as the default logs that are created).

WSMR and MCCDC have post-processing software that assists in developing metrics from scenario output. Lacking an UNCLASSIFIED post-processor, data management and analysis was time consuming. Additionally, correlation of data points was made difficult through naming conventions. Fields identified units by their names in one log, and by various identification numbers in others (i.e. observer_id, target_id, fire_id, etc.). Determining something such as the attacking unit, defending unit, weapon used, and result of an attack required cross validation between different logs. The naming conventions were held constant, though, meaning that the process could be automated to some degree.

2. Ease of Use: DAFS

DAFS was never developed to the level of distribution and continuous use that COMBATXXI was developed, and this is a notable obstacle in implementation. Scenario parameters are entered through Microsoft Access database files or XML format (Access was used in this scenario development).



munitionTyp	platformTyp	class	minRangePK	maxRangePK	minRange	maxRange
M249	Red_Infantry	dafs.weapon.LinearKillProbabi	0.9919	0.003190575	0	1000
AK47	Blue_Infantry	dafs.weapon.LinearKillProbabi	1	0.429115509	0	400
XM29	Red_Infantry	dafs.weapon.LinearKillProbabi	0.206575974	0.073832359	100	500
JAVELIN	Red_Infantry	dafs.weapon.LinearKillProbabi	0.99	0.66	65	2500

Figure 25. Sample DAFS input through Access spreadsheets

Though a library of sample scenarios provides insight into the schema for scenario development, data formatting was a concern. Certain aspects of DAFS are relatively arbitrary (i.e. geographical location or aggregation level of units) yet necessarily proportional. Changing a scenario parameter can have unpredictable effects on agent interactions unless the interrelation between parameters is understood. Documentation on scenario creation and consideration of variable connections is limited to the degree that it was often necessary to review the algorithms in Java code in order to determine the data structures and limitations. At one point in development, hard-coded parameters contradicted documentation. A limit placed on the minimum P_{kill} to enhance program stability caused weapon effects to be disregarded regardless of range. Without the requisite skill, a novice operator might not recognize the symptoms or understand the corrective action required.

DAFS output was similar to the output present in COMBATXXI, but greatly reduced due to fewer agents and limited built-in functionality. Though logging for complex situations would be straight-forward to develop, it is not inherent in the design. Based on the lesser number of agents and greatly simplified algorithms, there were far fewer interactions between agents. For example, runs of the scenario in DAFS produced a log similar to, but less detailed than, the ObserverLogger of COMBATXXI called the Acquisition log. This log for all 200 DAFS runs was composed of 43,258 rows of 16 columns of data (690,000 data points), which is approximately 15% of the size of the corresponding file for a single run of the same scenario in COMBATXXI. The Divining the causality of results was greatly simplified (and potentially easier to explain). Consequently, output processing times were substantially reduced when working with DAFS.

3. Lessons Learned

Translating high-resolution data into a low-resolution simulation is not simple. Several aspects of data analysis and correlation that were critical to completing this study made DAFS scenario development more difficult without necessarily contributing to the exploration of the problem space. In retrospect, many of these difficulties could have been avoided for an exploratory analysis. These difficulties consisted included the following:

- The use of the ACV Phase 0 scenario was difficult due to artifacts remaining from the primary study. A custom scenario could have been built and used more easily than adapting from an existing scenario, especially if the goal is developing a systematic approach for future work in this realm.

- Initial conditions play a huge role in determining the course of the scenario. This scenario begins with friendly and enemy units within sensor range of each other.
- Sensing is a difficult problem. The methodologies behind cognitive models cannot be partially implemented easily.
- Calibration of two models using different units of measurement requires attention to detail. As DAFS offers the flexibility to define most units as required by the goals of the analysis, coordination with respect to parameter scaling and parameter interaction requires attention to details. During scenario development, this was a source for multiple anomalies.
- When dealing with massive amounts of data, a dedicated data analysis tool would likely speed processing significantly. Excel is only marginally capable in this regard. Data sorting and elimination of extraneous values is essential. Implementing data mining techniques would be invaluable.
- Scaling of weapon effects is crucial. During initial scenario trial runs, each individual Marine agent in DAFS was mistakenly assigned 100% of the capabilities of the M249 and XM29. This was equivalent to estimating that every single Marine would be equipped with all available weapons and engage enemies with every weapon simultaneously (physically impossible). Additionally, someone is moving or communicating rather than shooting at any given time.

C. STATISTICAL COMPARISON

These two models represent reality in vastly different ways. Estimation of the validity of simplifying a complex scenario for simplistic representation was based on the following results.

1. Battle Metrics

One direct comparison between combat models is to contrast the survivors of the battle and the time of battle. In this section, the two models are contrasted based on the average and standard deviation between the 200 DAFS runs and 10 COMBATXXI runs. Though the models concur that the blue (Marine) units in the scenario should be victorious, the differences are obvious. While observing trial runs in COMBATXXI, it was noted that at some point the blue and red units would cease engaging each other and proceed to pass each other. It appears that in COMBATXXI, the enemy units became combat-ineffective after some degree of attrition (approximately 60%) which apparently equates to being destroyed in DAFS. Battle time was judged to be the time required from the first shot being fired until the last shot was fired.

	COMBATXXI	DAFS
Blue Casualties (%)	0.18	0
Red Casualties (%)	59.9	100
Min Battle Time	7.218 minutes	.30 minutes
Mean Battle Time	7.643 minutes	1.208 minutes
Max Battle Time	8.229 minutes	2.566 minutes

Table 7. Battle metrics contrasting COMBATXXI and DAFS results.

Sensor capability contrast included the attempt to aggregate the effects of the COMBATXXI cognitive model through a relatively simplistic rate of detection in DAFS. Though the application of the approximate distribution in DAFS produced a similar distribution to chosen metric in COMBATXXI, the magnitude of binocular detections in DAFS (Table 10) is excessive. This magnitude far exceeded the mathematical model predictions previously discussed in translation. The cause of the unexpected peak in binocular detections in DAFS was not determined, and remains a point for further investigation. This may account, in part, for the shorter DAFS battle durations due to the

DAFS entities being able to engage enemy units earlier than their COMBATXXI counterparts.

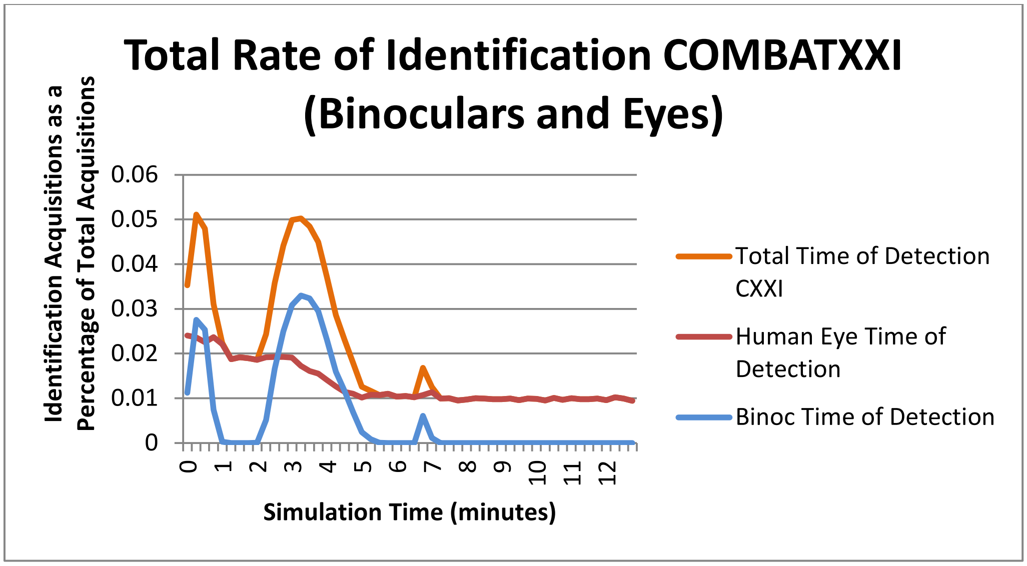


Figure 26. COMBATXXI experimental rates of acquisition to the level of identification in Phase 0 scenario.

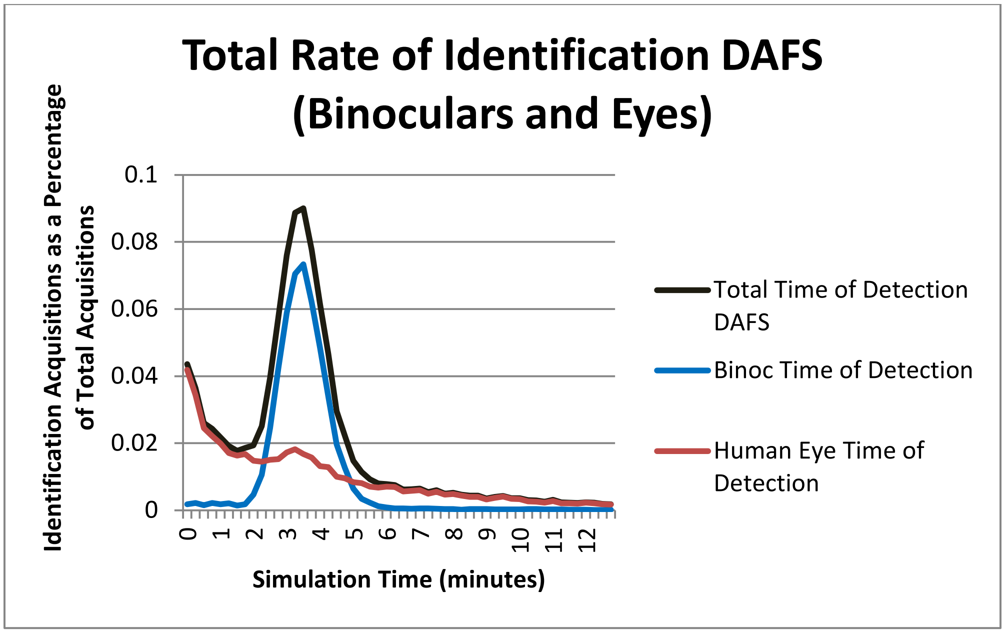


Figure 27. DAFS experimental rates of detection in Phase 0 scenario.

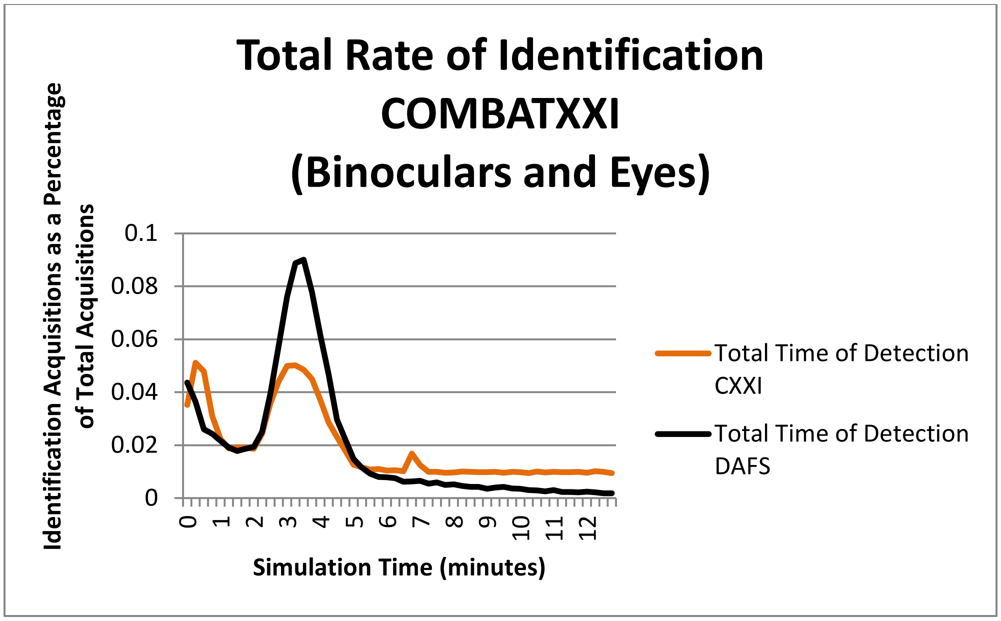


Figure 28. A contrast between COMBATXXI and DAFS rates of target acquisition based on COMBATXXI acquisition to level of identification and DAFS detection.

It would also be necessary to further explore the effects of sensors and detection in different scenarios in order to fully realize the capabilities and difficulties associated with general analysis. The fact that all entities began the scenario within sensor range of each other did not allow for a realistic development of initial detections. This technique of mimicking sensor distributions was not evaluated under conditions outside of sensor range, and further work would need in order to utilize DAFS in other scenarios.

2. Computational Demands

Computational demands in this study refer to the time required for simulation run computation. Simulation load times were not included in the time to complete the runs. The 20 COMBATXXI runs were contrasted with 200 DAFS runs to assess expected time to develop output per individual run. This contrast is not an even comparison, because the COMBATXXI scenario included many more units, control measures, and behaviors for entities beyond the scope of the area of interest for the study. This was by design, in that DAFS could potentially be used to assess a portion of a scenario without including the whole.

COMBATXXI runtime execution incorporated the option to run the simulation on multiple computing cores simultaneously. An interesting side effect was that the computational time required for a batch of runs was similar to the amount of time required to process a single run divided by the number of computational cores available. Though COMBATXXI recognized the number of virtual cores available (8 virtual cores), the performance per run was approximately half as good as when using the number of actual cores (4 actual cores) in trial runs. The 20 runs also did not divide evenly by 8 virtual cores, which made for interesting results. DAFS appeared to perform similarly when 4 separate instances of the program were started simultaneously, but these attempts were merely exploratory. For the sake of this experiment, both DAFS and COMBATXXI were run as designed.

COMBATXXI completed each of 20 runs with a mean time per run of 12.9 minutes (SD 2.08), but due to the multiple core implementation required a total time of 64.4 minutes to complete. Thus, executing a batch took approximately 3.2 minutes per run (even though a batch will take at least as long as the slowest run, regardless of core availability).

DAFS by contrast was used to complete 200 runs of the same approximate scenario. Using a single instance of the program, it required significantly less time than that of COMBATXXI to execute with a total time of 62.24 seconds or .31 seconds per run (SD .061).

D. SCENARIO AOA EXPLORATION

Contrasting the different routes of attack in DAFS was possible through a set of minor scenario changes to reflect new waypoints for the Marine units. This allowed for an attempt at executing a rapid prototype in the frame of AOA exploration. The results of this exploration were statistically similar, with the western-most route showing only the slightest trend toward longer battle times.

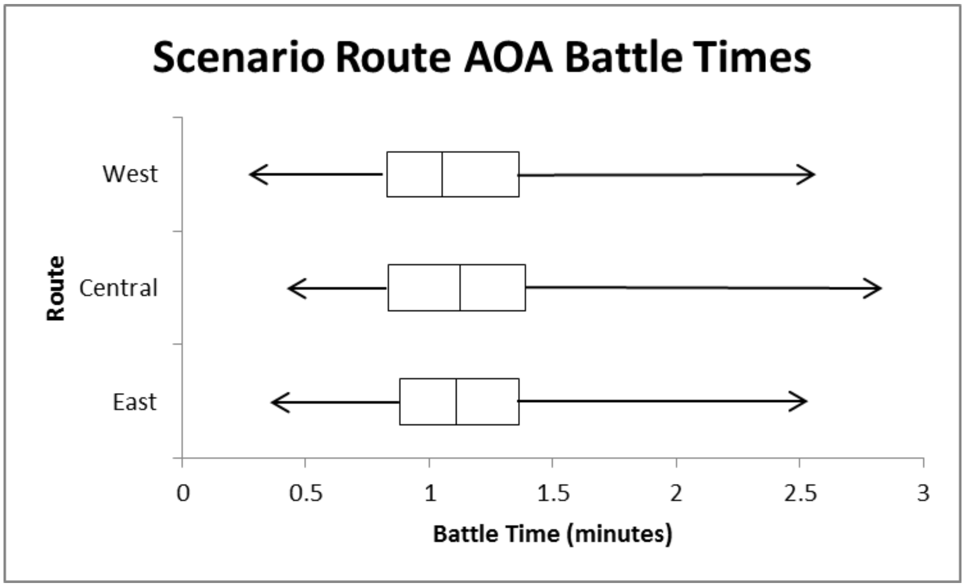


Figure 29. DAFS AOA of Phase 0 battle time based on different routing for Marines. The eastern route was the same routing as the COMBATXXI scenario.

The expected losses for each route were similar as well, with the central and western routes indicating only slightly increased potential for loss to the Marine units. This could potentially be related to the limited weapon range for enemy units. The eastern and western routes remain outside of enemy weapon range longer, while the central route more quickly requires the Marine agents to move into range of all three enemy platoons nearly simultaneously.

	Eastern Route	Central Route	Western Route
Blue Casualties (%)	0	3.71	0.5
Max Blue Casualties	0	8	7
Red Casualties (%)	100	100	100

Table 8. Casualty comparison based of DAFS Phase 0 AOA based on various routing

E. CONCLUSION AND RECOMMENDATIONS

COMBATXXI and DAFS use very different methodologies. Using them in tandem for rapid prototyping, quick-turn analysis, AOA exploration, or developing initial conditions will take a great deal of effort and is currently not feasible without further development. With some effort to improve interconnectivity and usability, there is potential for using DAFS to rapidly identify aspects in COMBATXXI scenarios needing further investigation during development.

1. Regarding Ease of Use

COMBATXXI and DAFS both require a significant amount of effort to develop, run, and analyze combat scenarios. The efforts are not entirely dissimilar, and data developed for one simulation may be portable into the other. For this to be done on a regular or larger scale, the process would benefit immensely from some sort of automation in translation. The translation techniques used here were time consuming and potentially unacceptably inaccurate.

Different naming conventions made tracing effects through logging files difficult in COMBATXXI. The MCCDC scenario was artfully designed in one respect. All units are assigned numeric designators for reference in logs. The Marine units were given 4 digit identifiers while the enemy units were given 5 digit identifiers. This differential decreased analysis time requirements. Without referencing other multiple log files at once, determining the specific unit responsible for firing a specific round at a specific target was difficult to determine otherwise. When attempting to tune the DAFS scenario by referencing these files, this aspect greatly increased development time. MCCDC has an initiative in place to develop an unclassified post-processing application (Sawyer, A., personal communication, June 2012) which would potentially streamline this process significantly.

DAFS was fast to run, but developing a scenario took a significant amount of effort in researching the required data types and interconnections by accessing the computer code directly. A complete and thorough users' manual would be essential to routine model implementation. There is a terrific potential in how quickly a scenario could be developed if translated data and a simplified (or better understood) user interface was immediately available. It would not be unreasonable to develop, run, and analyze a similar scenario in less than 1 hour if all of these preconditions could be established.

2. Regarding Statistical Comparison

The two models were statistically dissimilar in raw results. There was agreement in the Boolean sense that both models concur as to the ultimate conclusion, however. Losses were similar as well, though more exploration in different scenarios would be required to validate this technique as a means for useful comparison. Sensor and weapon effects data errors may have contributed to this error.

One potential source of error was using data for weapons not extrapolated from COMBATXXI. The data used was based on a different source and weapon profiles than those used in COMBATXXI. For example, the DAFS linear kill probabilities are an estimation of actual weapon performance. The true probabilities to kill for weapons are surely not linear, but distributed based on the type of weapon. Additionally, weapon effects were reduced by 1/5th in order to account for those elements of units not firing their weapons during that moment of combat. This did increase battle durations, but was still not similar to the COMBATXXI results.

The approximation of sensing may have introduced two separate errors, but it is unknown whether they affected results significantly. Admittedly, the approximation of sensing into DAFS was a rough approximation. This error was discussed previously. More importantly, the methodologies may not be accurately represented in DAFS via this means. In DAFS, detection equates to the ability of an agent to engage a target. Detection also is less transient in DAFS, meaning that a target is only detected once if it does not leave sensor range. COMBATXXI allowed for multiple identifications of the same target. It is not clear if identification carries the exact same context in COMBATXXI as detection does in DAFS.

Computational effort was significantly reduced in DAFS than in COMBATXXI. It took less time to run 200 replications in DAFS than it took to run a single replication in

COMBATXXI. In fact, extrapolated over the average values, more than 2400 DAFS replications could be run in the same time as one replication of the same scenario in COMBATXXI. A benefit of performing more replications is that the distribution of potential values can be better developed. When runs are few, possible outcomes can be overlooked. Additionally, AOA must be proportionally limited. Even as a precursor to further scenario development, the low overhead in computation (and associated analysis) could be of a significant financial and temporal advantage in most situations.

3. Regarding AOA Exploration

The AOA exploration was simple to implement, once the scenario parameters were implemented into DAFS. It was as easy as adding different waypoints to the control measures for the Marines and rerunning the scenario. The results were not significantly different with regards to the time of battle, but the losses suffered by the Marine units were different based on routing. Though the losses were small, this indicated an area for concern or further exploration. The shorter routing toward the enemy put Marines in a position of slightly increased hazard to enemy fire. Although this may be obvious to even a novice tactician, this is a simple scenario. Results such as this in a larger, more complex scenario could easily be overlooked. It is exactly the type of simple, useful insight that DAFS might provide model developers such that they can rapidly, economically identify and analyze conflicting results.

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VI. FUTURE WORK

Optimally, the effects of implementing DAFS in a parallel development environment with a current study at WSMR or MCCDC could yield results as to the efficacy of either evolutionary or rapid, throw-away prototyping and explore the benefits of a broader, quick-turn COA assessment associated with scenario development. It is possible that the cost of developing prototypes would be offset by later savings in study development. This technique reflects the ethos of Marine Corps machine gunners' statement, "slow is smooth, and smooth is fast." With less time and money available to make mistakes, more effort should be put into making less mistakes (realizing that smooth actions make execution faster). As machine gunners accomplish their goals through practice, effectively prototyping could be used as practice for final model development.

There is also the potential for creating a variable resolution simulation that could be dynamically modified to represent more or less detail. Considering the amount of processing required to run and analyze more complex models, it might be valuable to experiment with rapid prototyping capabilities within a model available through run-time options. Including additional functionality in a complex system might be prohibitively difficult, though.

One of the most interesting potentials for future work was in the area of sensing algorithms. During the efforts to convert the scenario from COMBATXXI to DAFS, the concept of using a sum of exponentially distributed variables to represent the cognitive process in COMBATXXI was attempted. Sensor detections and many other Poisson-like processes can be represented to some degree through exponential distributions. First, the average time to gain the four levels of acquisition was used as the parameter for a gamma distribution, but this assumes the exponential means are all the same (which they were not). Dr. Buss developed a simple code addition to DAFS to model the phenomenon that would accept multiple exponential distributions of various means as an input to develop a single resulting detection algorithm. This technique was especially attractive in that it represents the relatively complex cognitive process associated with target acquisition in a relatively simple manner. Though it would require four random number draws (as opposed to the two required for the representation used in this thesis), this technique would still be relatively low-cost in terms of computational effort while producing a very wide range of results based on the settings for each level of detection.

Additional work would be required to analyze and evaluate the techniques used here if they were to be applied to general analysis. Entities in this study were all located within sensor range of each other. It is likely that the distributions for detections occurring throughout sensor ranges, including entities that enter sensor range during the scenario, would be handled differently in COMBATXXI and DAFS. If DAFS is to be used to prototype scenarios for COMBATXXI, the technique involving the use of approximate distributions would need to be further explored.

Computational complexity and resource constraints are related. A study contrasting the relative resources required per agent could easily be pursued along the same lines as this study. As COMBATXXI is currently a production model with libraries of vetted scenarios, it would be a logical choice. Simple unit dynamics would need to be maintained to limit the effects of additional command structures and controls. By gradually adding units to a scenario, the relative effort required to run and process the output could be contrasted.

Finally, DAFS could benefit significantly from continuous use. This leads to continual development and bug repair. A more thorough and straight-forward user's manual for the entry level user would be extremely valuable. Though the flexibility in scenario development is related to the user's ability to define parameters in relative terms, the interrelations between data elements is not completely obvious or enforced through strong data typing.

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